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First Named Inventor Shree K. Nayar et al.

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Assistant Commissioner for Patents  
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Sir:

Enclosed herewith for filing is a patent application of SHREE K. NAYAR and TOMOO MITSUNAGA  
entitled APPARATUS AND METHOD FOR HIGH DYNAMIC RANGE IMAGING USING SPATIALLY  
VARYING EXPOSURES

which includes:

☒ Specification 35 Total Pages  
☒ Claims 18 Total Pages  
☒ Abstract 1 Total Pages  
☒ Drawing(s) 25 Total Sheets  
       formal  
    X informal

☒ Combined Declaration and Power of Attorney 3 Total Pages

☒ Newly executed (original or copy)

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(for continuation/divisional only - **must be filed to avoid surcharge for late filing**)

If a continuing application, check appropriate box:

☐ Continuation ☐ Divisional ☐ Continuation-In-Part (CIP)  
of prior application No.       

☐ Amend the specification by inserting, before the first line, the following sentence:

"This is a ☐ continuation ☐ divisional ☐ continuation-in-part  
of copending application Serial No.    filed   ."

Attorney Docket No. A32368-070050.0998

- ☐ An Assignment of the invention to \_\_\_\_.
- ☐ is attached. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.
- ☒ will follow.
- ☐ has been filed in the prior application
- ☐ Small Entity Statement(s)
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- ☐ Cancel in this application original claims \_\_\_\_ of the prior application before calculating the filing fee.

The filing fee has been calculated as shown below:

FOR	(Col. 1) <u>No. Filed</u>	(Col. 2) <u>No. Extra</u>	Small Entity <u>Rate</u>	<u>Fee</u>	OR	Other Than A Small Entity <u>Rate</u>	<u>Fee</u>
Basic Fee							\$760
Total Claims	64	-20 = 44	x \$9 =	\$0		x \$18 =	\$792
Ind. Claims	5	-3 = 2	x \$39 =	\$0		x \$78 =	\$156
Multiple Dependent Claim		0	+ \$130 =	\$0		+\$260 =	\$0
			Total	<u>\$0</u>			<u>\$1,708</u>

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Fee Payment Being Made:

☒ Enclosed

☒ Basic filing fee

\$1,708.00

☐ Recording Assignment

[\$40.00; 37 CFR 1.21(h)]

Total Fees Enclosed

\$1,708.00

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Priority

- ☐ Priority of application Country \_\_, Appln. No. \_\_ filed \_\_ is claimed under 35 U.S.C. 119.
- ☐ Certified Copy of Priority Document(s) Country \_\_, Appln No. \_\_, filed \_\_.
- ☐ is/are attached ☐ will follow ☐ has been filed in the parent application S/N \_\_.
- ☒ The Commissioner is hereby authorized to charge payment of any additional filing fees required under 37 CFR 1.16, 1.17, and 1.21(h) associated with this communication or credit any overpayment to Deposit Account No. 02-4377. Two copies of this sheet are enclosed.

BAKER & BOTTS, L.L.P.

By Henry Tang  
Henry Tang

PTO Registration No. 29,705

Enclosures

BAKER & BOTTS, L.L.P.

30 ROCKEFELLER PLAZA

NEW YORK, NEW YORK 10112

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TO ALL WHOM IT MAY CONCERN:

Be it known that WE, Shree K. Nayar, a citizen of the United States residing in County of New York, State of New York, and Tomoo Mitsunaga, a citizen of Japan, residing in County of New York, State of New York, whose post office addresses are, respectively, 560 Riverside Drive, New York, NY 10027, and 140 West 69<sup>th</sup> Street, New York, NY 10023, have invented an improvement in

APPARATUS AND METHOD FOR HIGH DYNAMIC RANGE IMAGING USING SPATIALLY  
VARYING EXPOSURES

of which the following is a

BACKGROUND OF INVENTION

The present invention relates to apparatus and method for capturing an image of a scene, and, more particularly, to apparatus and method for capturing a high dynamic range image using a low dynamic range image sensor.

Virtually any real world scene produces a very large range of brightness values. In contrast, known image sensing devices have very limited dynamic ranges. For example, it is typical for a video sensor to produce 8-bits or less of grey-level or color information. In the case of grey-scale images, 8-bits provide only 256 discrete grey levels, which is not sufficient to capture the fine details of most real life scenes.

A known solution to the problem of capturing high dynamic range images with a low dynamic range image sensor is to take multiple image measurements for each local scene area while varying the exposure to light from the scene. Such exposure variation is typically accomplished by sequentially taking multiple images of the scene with different exposures and then combining the multiple images into a single high dynamic range image. Temporal exposure variation techniques for enlarging the dynamic range in imaging a scene may be found for example in: U.S. Patent 5,420,635 to M. Konishi et al., issued May 30, 1995; U.S. Patent No. 5,455,621 to A. Morimura, issued October 3, 1995; U.S. Patent No. 5,801,773 to E. Ikeda, issued September 1, 1998; U.S. Patent No. 5,638,118 to K. Takahashi et al., issued June 10, 1997; U.S. Patent No. 5,309,243 to Y.T. Tsai, issued May 3, 1994; Mann and Picard, "Being 'Undigital' with Digital Cameras: Extending Dynamic Range by Combining Differently Exposed Pictures," Proceedings of IST's 48<sup>th</sup> Annual Conference, pp. 422-428, May 1995; Debevec and Malik, "Recording High Dynamic Range Radiance Maps from Photographs," Proceedings of ACM SIGGRAPH, 1997, pp. 369-378, August 1997; and T. Misunaga and S. Nayar, "Radiometric Self Calibration," IEEE Conference on Computer Vision and Pattern Recognition (CVPR 99), June 1999. However, techniques that require acquiring multiple images while temporally changing the exposure have the fundamental problem in that variations in the scene may take place between exposure changes. In other words, these techniques are useful only for static scenes where the scene radiance values stay constant. Moreover, between exposure changes the position and orientation of the imaging device and its components must remain constant. Finally, because a greater time is needed to sequentially capture all the required images, the temporal exposure variation techniques are not suitable for real time applications.

Another known solution to the problem of capturing high dynamic range images with a low dynamic range image sensor is to simultaneously capture multiple images of a scene using different exposures. Such a technique is disclosed, for example, in Yamada et al., "Effectiveness of Video Camera Dynamic Range Expansion for Lane Detection," Proceedings of the IEEE Conference on Intelligent Transportation Systems, 1997. Typically, two optically aligned CCD light-sensing arrays are used to simultaneously capture the same image of a scene with different exposures. Light from the scene is divided by a beam splitter and directed to both CCD light-sensing arrays. The two captured images are combined into one high dynamic range image by a post processor. This technique has the disadvantage of requiring complex and expensive optics, and capturing images with more than two different exposures becomes difficult.

Efforts have been made to increase the dynamic range of charge-couple imaging devices. Published Japanese patent application No. 59,217,358 of M. Murakoshi describes using two or more charge coupled device (CCD) light-sensing cells for each pixel of the imaging device. Each of the light-sensing cells of a pixel have different photo sensitivities so that some cells will take longer to reach saturation than others when exposed to light from a scene. In this manner, when the store photogenerated charge in all of the light-sensing cells of a pixel are combined, the dynamic range of the pixel is effectively increased. However, the Murakoshi reference does not address the problem of capturing high dynamic range images using a low dynamic range image sensor.

U.S. Patent No. 4,590,367 to J. Ross et al. discloses an arrangement for expanding the dynamic range of optical devices by using an electrically controlled light modulator adjacent to the light-sensitive area of an optical device to reduce the brightness of incident light from an imaged optical scene so as to

not exceed the dynamic range or the light-sensitive area. The light modulator of the Ross et al. reference has individual pixel control of light amplification or attenuation in response to individual control signals. The detected level of light intensity emerging from each pixel of the modulator is then used to develop the control signals to adjust the amplification or attenuation of each pixel of the modulator to bring the brightness level into the detector's rated dynamic range. Thus, wide input light intensity dynamic range is reduced to a narrow dynamic range on a pixel-by-pixel basis. However, the apparatus and method of the Ross et al. reference is aimed at simplifying three-dimensional measurement using projected light, and there is nothing in the reference on how to capture a high dynamic range image.

Another problem of known systems for capturing high dynamic range images is the display of such images using low dynamic range displays. Most commercially available displays, such as video monitors, televisions and computer displays, have low dynamic ranges. Hence, after the high dynamic range image is obtained, one needs to use a mapping method to display the image on a low dynamic range display while preserving the pertinent visual information. In other words, the dynamic range of the captured image must be compressed while preserving visual details of the scene.

A known technique for compressing the dynamic range of a captured image is tone curve (or response curve) reproduction, in which a high dynamic range color scale is mapped into a low dynamic range color scale using an appropriate tone curve. Logarithmic scale conversion and gamma correction are examples of this kind of compression. However, tone curve reproduction compression does not preserve visual details of the scene.

A more sophisticated tone curve reproduction technique is histogram equalization, which creates a tone curve by integrating the color histogram of the image. Histogram equalization results in a more

even redistribution of the colors in the image over the space of colors, but this technique cannot sufficiently preserve the detail of an image which has several local areas with very bright (or very dark) pixels, where such local areas together may span the complete range of grey levels. Hence, details within individual areas are not enhanced by the histogram equalization process.

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Another technique for compressing the dynamic range of a captured image is disclosed in Pattanaik et al., "A Multiscale Model of Adaptation and Spatial Vision for Realistic Image Display," SIGGRAPH 98 Proceedings, pp. 287-298, 1998. This technique divides the image data into several frequency component images, for example, in a Laplacian pyramid. The image is then re-composed after each frequency component has been modulated in a different manner. An advantage of this technique is that absolute pixel values do not contribute so much, unlike histogram equalization. However, this technique has the drawback of requiring large amounts of memory and extensive computations to obtain the frequency component images.

Accordingly, there exists a need for an apparatus and method for capturing high dynamic range images using a relatively low dynamic range image sensor and for detail preserving compressing the captured high dynamic range image for display by relatively low dynamic range display device, which overcomes the problems of the prior art as discussed above.

#### SUMMARY OF THE INVENTION

In accordance with the present invention, there is provided a system for high dynamic range imaging comprising an image sensor having an array of light-sensing elements. The image sensor senses the image of a scene and provides corresponding pixel values representing the light intensities impinging on each of the light-sensing elements thereof. The image sensor provides a saturated pixel

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value when the intensity of light impinging on a corresponding light-sensing element is greater than a first threshold value and provides a blackened pixel value when the intensity of light impinging on a corresponding light-sensing element is below a second threshold level. The image sensor has a low dynamic range relative to the range of light intensities in the optical image of the scene.

5           The system includes a mask interposed between the scene and the image sensor. The mask has a multiplicity of light transmitting cells, each controlling the exposure of a respective one or more of the light-sensing elements of the image sensor to light from the scene. Each of the light-sensing elements having a corresponding exposure value determined by the transparency of the cell through which light impinging on the light-sensing element passes.

          The system further includes a first memory storing exposure values corresponding to the light-sensing elements and an image processor coupled to the image sensor for receiving the pixel values provided thereby and coupled to the first memory for receiving the exposure values corresponding to the light-sensing elements. The image processor has a normalizer for mapping the pixel values by a function of the exposure values to derive corresponding normalized pixel values. An example of such mapping is to divide each of the pixel values by a respective exposure value.

          According to a first exemplary embodiment of the present invention, the exposure values corresponding to the light-sensing elements are fixed and the image processor further includes an interpolator for interpolating the normalized pixel values to derive interpolated pixel values at respective positions in a second array overlapping the array of light-sensing elements. The interpolation process  
20       may omit normalized pixel values that correspond to saturated pixel values or blackened pixel values.

Where the response function of the image sensor is not linear, the system may include a second memory for storing the response function of the image sensor, and the image processor is coupled to the second memory for receiving the response function and further includes calibration means for linearizing the pixel values provided by the image sensor in accordance with the response function before the pixel values are normalized by the normalizer.

According to a second exemplary embodiment of the present invention, the exposure value of each cell of the mask is alterable by applying a respective exposure control signal to the mask. The system includes a mask controller coupled to the image sensor for receiving the pixel values provided thereby and for computing, and applying to the mask, exposure control signals for minimizing the number of saturated pixel values and blackened pixel values from the corresponding area of the image sensor, and providing exposure values corresponding to the applied exposure control signals. The normalizer then normalizes each of the pixel values from the image sensor to derive normalized pixel values which represent a radiance image of the scene.

The dynamic range of the captured high dynamic range image is compressed to allow viewing on a display having a relatively low dynamic range by providing a smoother coupled to an exposure pattern memory for receiving exposure values stored therein and applying a smoothing filter to the exposure values to derive smooth exposure values corresponding to the normalized pixel values. Also provided is an exposure reapplicator coupled to the normalizer of the image processor for receiving the normalized pixel values and for multiplying each of the normalized pixel values with a corresponding smoothed exposure value to derive monitor image pixel values of an image having compressed dynamic range but without substantial loss of image detail.

In an alternative implementation of the first exemplary embodiment of the present invention, a mask is not used but the array of light-sensing elements of the image sensor has a spatially varying pattern of photosensitivities to incident light and corresponding photosensitivity values indicative of the respective photosensitivities. The photosensitivity values are stored in the first memory and are used by the normalizer in conjunction with respective pixel values from the image sensor to derive corresponding normalized pixel values, and there is provided an interpolator for interpolating the normalized pixel values to derive interpolated pixel values at positions in a second array overlapping the array of light-sensing elements.

In accordance with another aspect of the present invention, there is provided a method for high dynamic range imaging comprising the steps of exposing an image sensor having an array of light-sensing elements to an image of a scene using a spatially varying exposure. The image sensor senses the image and provides corresponding pixel values representing light intensities impinging on respective ones of the light sensing elements. The image sensor provides a saturated pixel value when the intensity of light impinging a respective light-sensing element is greater than the first threshold level and providing a blackened pixel value when the intensity of the light impinging on a respective light-sensing element is below a second threshold level. The image sensor having a low dynamic range relative to the range of light intensities in the image of the scene. The method further comprises the step of normalizing the pixel values provided by the image sensor using respective exposure values to derive corresponding normalized pixel values.

According to one implementation of the method, the step of exposing the image sensor using a spatially varying exposure includes the step of using a mask having a multiplicity of light-transmitting

cells each controlling the exposure of a respective one or more of the light-sensing elements to light from the scene. Each of the light-sensing elements having a corresponding exposure value indicative of the transparency of the cells through which light impinging on the light-sensing element passes, and the step of normalizing the pixel values provided by the image sensor includes the step of mapping the pixel values by a function of the exposure values.

In another implementation of the method, the exposure values corresponding to the light-sensing elements are fixed, and the method further comprises interpolating the normalized pixel values to derive interpolated pixel values at respective positions of a second array overlapping the array of the light-sensing elements.

In a further implementation, the method comprises the step of calibrating the pixel values provided by the image sensor according to a response function of the image sensor to linearize the pixel values before the step of normalizing the pixel values.

In still another implementation of the method, the exposure value corresponding to each of the light-sensing elements is alterable by applying a respective exposure control signal to the mask. The method further comprises the steps of computing from the pixel values provided by the image sensor exposure control signals for minimizing the number of saturated pixel values and blackened pixel values from the image sensor, and applying the computed exposure control signals to the mask, as well as providing exposure values corresponding to the applied exposure control signals for use in the normalizing step.

In a still further implementation, the method comprises the step of applying a smoothing filter to the exposure values corresponding to the applied exposure control signals to derive smoothed exposure

values corresponding to the normalized pixel values. The smoothed exposure values are then reapplied to the normalized pixel values by multiplying each normalized pixel value with a corresponding smooth exposure value to derive monitor image pixel values representing an image having compressed dynamic range but with visual details of the image preserved.

5           In accordance with still another aspect of the present invention, there is provided a method for high dynamic range imaging comprising the steps of exposing a frame of photographic film in a film camera to an image of a scene through a planar mask disposed between the shutter and the focal plane of the camera. The mask has a multiplicity of light transmitting cells each controlling the exposure of a respective region of the film. Each of the cells of the mask has an associated exposure value indicative of the transparency of the cell. The exposure values are stored in an exposure pattern memory. The exposed film is then processed to contain a masked image of the scene. The masked image contained on the film or a print thereof is scanned to obtain pixel values representative of the different regions of the masked image exposed on the film through the cells of the mask. The masked image, as represented by the pixel values, is aligned with the mask as represented by the exposure values such that each pixel value corresponds to an exposure value associated with the mask cell through which the region represented by the pixel value was exposed. The pixel values are then normalized using corresponding exposure values to derive normalized pixel values disposed at respective positions of a first array.

15           In one implementation of the method, there is included the further step of interpolating the normalized pixel values to derive interpolated pixel values at respective positions of a second array  
20           overlapping the first array. In another implementation of the method, there is further included the step

of calibrating the pixel values according to a combined response function of the film and of the image sensor used to scan the masked image contained on the film.

### BRIEF DESCRIPTION OF DRAWINGS

For a more complete understanding of the nature and benefits of the present invention, reference should be made to the following detailed description taken in conjunction with the accompanying drawings, in which:

Fig. 1 is a functional diagram of an imaging system according to a first exemplary embodiment of the present invention;

Fig. 2 is a block diagram of the hardware components of a video camera implementation of the imaging system of Fig. 1;

Fig. 3 is a data flow diagram of the image processor of the system of Fig. 1;

Fig. 4A is a plan view of the patterned mask used in the system of Fig. 1;

Fig. 4B depicts a group of four neighboring cells that are repetitively disposed to form the mask pattern of Fig. 4A;

Fig. 5A depicts the imaging optics, the mask and image sensor of the system of Fig. 1 and objects in a scene whose image is being captured;

Fig. 5B depicts the image of the objects of the scene as viewed through the patterned mask of Fig. 4A;

Fig. 6 are diagrams illustrating calibration and normalization as carried out by the system of Fig. 1 on four neighboring pixel values as detected through four neighboring cells of the mask;

Fig. 7 are diagrams illustrating calibration and normalization as carried out by the system of Fig. 1 on four neighboring pixel values as detected through four neighboring cells of the mask, where one of the pixel values is a blackened pixel value;

Fig. 8 are diagrams illustrating calibration and normalization as carried out by the system of Fig. 1 on four neighboring pixel values as detected through four neighboring cells of the mask, where two of the pixel values are saturated pixel values;

Fig. 9 are diagrams illustrating interpolation as carried out by the system of Fig. 1, in particular the application of a  $2 \times 2$  interpolation filter to every  $2 \times 2$  pixel local area of the masked image to derive interpolated pixel values;

Fig. 10A is a diagram depicting the original image grid having light-sensing elements of the image sensor disposed at respective intersections thereof superimposed on an interpolation grid;

Fig. 10B illustrates an interpolation filter applied to each different two pixel by two pixel region of the original image grid to derive interpolated pixels at respective intersections of the interpolation grid;

Fig. 11 is a flow diagram of the operation of the image processor of the system of Fig. 1;

Fig. 11A is a flow diagram illustrating in greater detail the calibration step 208 of the flow diagram of Fig. 11.

Fig. 12 is a functional block diagram of an imaging system according to a second exemplary embodiment of the present invention;

Fig. 13 is a block diagram depicting the hardware components of a video camera implementation of the imaging system of Fig. 12;

Fig. 14 is a diagram depicting the arrangement of the optical components, the mask, a light diffuser and the light-sensing array of the system of Fig. 12;

Fig. 15 is a diagram illustrating the correspondence of mask cells and the pixel positions of the image sensor of the system of Fig. 12;

Fig. 16 are diagrams illustrating the operation of the mask controller of the system of Fig. 12 in adaptively controlling the exposure values of the mask;

Fig. 17 is a flow diagram of the operation of the mask controller of the system of Fig. 12;

Fig. 18 is a data flow diagram of the image processor of the system of Fig. 12;

Fig. 19 are diagrams illustrating the smoothing operation of the exposure values and the reapplication of the smoothed exposure values to the captured high dynamic range image pixel values in the system of Fig. 12;

Fig. 20 is a flow diagram of the exposure value smoothing operation carried out by the system of Fig. 12;

Fig. 21 is a diagram representing an example of a smoothing filter useable in the smoothing operation of Fig. 20;

Fig. 22 is a functional diagram of an imaging system according to a third exemplary embodiment of the present invention;

Fig. 23 is a diagram depicting the detailed structure of the aligner of the imaging system of Fig. 22; and

Fig. 24 is a flow diagram of the operation of the aligner of the imaging system of Fig. 22.



DETAILED DESCRIPTION

Referring now to Fig. 1, there is shown a functional diagram of an imaging system 100 according to a first exemplary embodiment of the present invention. The system 100 includes a mask 101 through which incident light 2 from a scene (not shown) passes before impinging on an image sensor 3. The image sensor 3 senses an image of the scene as transmitted by the mask 101 and provides corresponding pixel values to an image processor 4, which is coupled to a response function memory 6 and an exposure pattern memory 5 and which provides high dynamic range image data to an output image memory 7. The mask 101 is a plate of transparent material which has neutral characteristics with respect to the wavelengths of the incident light and has a fixed spatial pattern of transparency in the region through which the incident light 2 passes. The term "light" as used in the specification and claims refers to electromagnetic radiation spanning the spectrum from the millimeter wave region to the gamma ray region. The image sensor 3 preferably comprises a charge coupled device (CCD) image detector having an array of light-sensing elements (not shown), but may be any other type of image sensor including photographic film. In general, the image sensor 3 will have a low dynamic range relative to the range of incident light 2 emanating from the scene. The response function data stored in memory 6 is the input/output characteristics of the image sensor 3, which has been previously measured and stored in the memory 6 as a look-up table, in parametric form or other appropriate data form. The exposure values stored in memory 5 are indicative of the transparency of the mask at each pixel position such that there is a corresponding exposure value for each pixel value provided by the image sensor 3. The exposure values were previously measured and stored in the exposure pattern memory 5 as raw or coded data. The image processor 4 derives high dynamic range image data from the pixel values provided by the

image sensor 3, the response function data stored in memory 6 and the exposure values stored in memory 5. The high dynamic range image data, which is stored in the output image memory 7, has radiance values proportional to corresponding radiance values of the scene.

Turning now to Fig. 2, there are shown the hardware components of a video camera implementation 200 of the system of Fig. 1. The camera of Fig. 2 has an image sensing part 401, which includes a lens arrangement 402 for focusing an image of a scene onto the photosensitive surface of a CCD light-sensing array 165, an aperture 403 for controlling the overall exposure of the image, a mask 101 positioned in close proximity to the CCD light-sensing array 165 and a preamplifier 404 for adjusting the CCD output and for reducing noise. The preamplifier 404 includes several analog circuits which are usually used in a video camera, such as a correlated double circuit, an automatic gain control circuit, a gamma correction circuit and a knee circuit. The camera implementation 200 of Fig. 2 also includes an image processing part 405 having an analog-to-digital converter 406 for digitizing the signals from the image sensing part 401 corresponding to the captured images. The digitized images are stored in a frame memory 407 which corresponds to the output image memory 7 in Fig. 1. Computation of the high dynamic range image data is carried out in a processing unit 411, which has access to the data in the frame memory 407, a ROM 409 and a RAM 410. The ROM 409 is used to store the exposure values and the response function data, as well as the instructions for processing unit 411. The computed high dynamic range image in the frame memory 407 is converted to an analog signal by a digital-to-analog converter 408, which provides the analog signal to a video output part 412. The video output part 412, which is only needed in a video camera implementation and has no counterpart shown

in Fig. 1, includes a video encoder 413 which encodes the converted analog image to a video signal. The video signal is then passed through an output unit 414 which provides a video output 415.

Fig. 3 shows a diagram 3000 of the data flow of the image processor 4 of Fig. 1. The image processor comprises calibrator 9, a normalizer 10 and an interpolator 11. The calibrator 9 maps image data 8 captured by the image sensor 3 into a linear response image by using the response function data stored in the response function memory 6. Then the normalizer converts the linear response image into an image which is proportional to the scene radiance. Finally, the interpolator 11 interpolates pixel values that cannot be computed because of saturation or blackening, and then provides the corrected image data to the output image memory 7. Interpolation may be used even in the absence of saturated or blackened pixels as a way of reducing noise. Fig. 4A shows an example of a mask pattern for the mask 101 used in the system of Fig. 1. In this mask example, the mask 101 is a two-dimensional array of cells with different transparencies (attenuations). The mask 101 consists of repetitively disposed identical groups of four cells having different transparencies. Fig. 4B shows the group of four cells 102, 103, 104 and 105, which is repetitively disposed to form the pattern of the mask 101 of Fig. 4A. The group has a brightest cell 102, a bright cell 103, a dark cell 104 and a darkest cell 105 with the brightest cell 102 being the most transparent and the darkest cell 105 being the least transparent of the four cells. While in the example of Figs. 4A and 4B, a group of four cells are repetitively disposed to form the exposure pattern of the mask 101, groups having fewer or more cells having differing transparencies may be similarly repeated to form the same or a different exposure pattern. The exposure pattern of the mask need not be periodic and may even be random in distribution of transparencies. Moreover, the mask 101 may be constructed from a material that has a non-linear optical response. Such a material would have a

transmittance (or attenuation) that varies in a non-linear manner with the intensity of the incident light. Such a mask would provide a detailed preserving optical filter that enhances the effective dynamic range of the imaging system while preserving visual details.

Where a solid-state image sensing device such as a CCD or CMOS light-sensing array is used, the mask pattern can be fabricated on the same substrate as the image sensing device using photolithography and thin film deposition, or the mask pattern may be formed by photolithography and etching of the device itself. In the case of a film camera, the mask may be positioned between the shutter and the plane of the film or be attached to the film itself. In lieu of the mask, the film itself may have a spatially varying light sensitivity. The checkered mask 101 lets every local area have four different exposures. Thus every local area is captured using the large dynamic range produced by the four different exposures. The exposure values of the cells in the checkered mask 101 are stored in the exposure value memory 5 to be used by the image processor 4.

Figs. 5A and 5B illustrate the capture of an image of a scene with the checkered patterned mask 101. As shown in Fig. 5A, a masked plate 101 is placed in front of an image sensing device 165, and the mask plate 101 is aligned so that each mask cell is positioned in front of a respective pixel (i.e., a light-sensing element) of the image sensing device 165. Incident light from the scene passes through the imaging optics 147, then focuses onto the image plane of the image sensor 3, but the light intensity which is attenuated by the masked plate 101 is recorded at each pixel position. Also shown in Fig. 5A is a scene having a bright object 106 and a dark object 107. Thus an image like the one shown in Fig. 5B is obtained when the scene is captured by the image sensing device 165 through the masked plate 101. It should be noted that even if pixels of brighter exposure are saturated in an area of the bright object 106,

pixels of darker exposure in the same area will still have values within the dynamic range of the image sensor 3. Similarly, even if pixels of darker exposure are too dark in an area of the dark object 107, pixels of brighter exposure in the same area will still have values within the dynamic range of the image sensor 3.

5            Fig. 6 illustrates an example of the processing that is carried out by the calibrator 9 and the normalizer 10 of the image processor 4. In this example, a local area 112 of four neighboring pixels is taken from a region 111 in the background of the scene. Since the background of the scene is of constant brightness, the radiance values of the four pixels 112 are the same. However, the measured values of the four pixels differ because of non-linearities in the response function of the image sensor 3 and the differences in the exposure values corresponding to the four pixel locations as a result of the transparency pattern of the mask. The diagram at the center of Fig. 7 shows the process of converting each of the measured pixel values to a pixel value that is linear with respect to the scene radiance, and normalizing of the linearized pixel values. First, the calibration means 9 applies the response function of the image sensor 3 represented by the solid line response curve 113 to each of the measured pixel values to remove the non-linearity of the image sensor 3, as represented by the dotted lines 114. Each of the calibrated pixel values is then divided by its corresponding exposure value, as represented by the dotted lines 115. The result is represented by the diagram 116, which shows four calibrated and normalized pixel values in neighboring pixel locations having the same radiance. While normalization as used in the example of Fig. 6 involves dividing a pixel value by its corresponding exposure value, it is  
20            contemplated that normalization encompasses any mapping of pixel values by a function of the exposure values.

Fig. 7 illustrates another example of processing by the calibration means 9 and the normalizer 10 of the image processor 4, but this time the processing is on four neighboring pixel locations 118 taken from a dark region 117 of the scene. In the example of Fig. 7, three of the pixel locations have pixel values in the dynamic range of the image sensor 3 but one of the pixel locations has a blackened pixel value. Calibration and normalization of the four pixel values is shown in the diagram at the center of Fig. 7. In the pixel value axis of the diagram, the blackened pixel threshold and the saturated pixel threshold are indicated by  $T_b$  and  $T_s$ , respectively. As shown in the diagram, the calibration and normalization process cannot be correctly applied to the blackened pixel value, as indicated by the broken line 119. Thus, the result of the calibration and normalization is represented by the diagram 120, which shows three calibrated and normalized pixel values having the same radiance and one blackened pixel value (marked with the letter "b") as to which calibration and normalization cannot be correctly applied.

Turning now to Fig. 8, there is shown yet another example of processing by the calibrator 9 and the normalizer 10 of the image processor 4, but this time the processing is on four neighboring pixel locations 122 taken from a bright region 121 of the scene. Two of the four pixel locations 122 have pixel values in the dynamic range of the image sensor 3 while the other two have saturated pixel values. Calibration and normalization of the four pixel values are illustrated by the diagram at the center of Fig. 8. Once again the blackened pixel threshold and the saturated pixel threshold are indicated by  $T_b$  and  $T_s$ , respectively, on the pixel value axis of the diagram. The two saturated pixel values cannot be correctly calibrated or normalized as indicated by the broken line 123. The result of the processing is represented

by the diagram 124, which shows calibrated and normalized pixel values of the same radiance at two pixel locations and saturated pixel values (marked with the letter “s”) at the other two pixel locations.

In accordance with the present exemplary embodiment, saturated or blackened pixel values are marked by the calibrating means 9 so that the interpolator 11 can treat such exceptions accordingly.

Fig. 9 illustrates the interpolation process as carried out by the interpolator 11 of the image processor 4. At the upper right hand portion of the figure, there is shown a  $10 \times 10$  group of pixels 126 representing the region 125 of the scene, which encompasses a boundary of dark and bright portions of the scene. The pixel values at the respective pixel locations 126 have undergone the calibration and normalization process described in connection with Figs. 6, 7 and 8 and all saturated pixel are marked with a black “x” and all blackened pixel values are marked with a white “x.” The interpolator applies a two pixel by two pixel interpolation filter to every different two pixel by two pixel region of the image pixel array. The interpolation filter computes an interpolated pixel value at the center of each two pixel by two pixel region by taking the average of non-saturated and non-blackened pixel values in the region. Since every different two pixel by two pixel region is exposed through four different transparencies of the mask, there will generally be at least one non-saturated and non-blackened pixel value in each region. At the position of the interpolation filter 127 shown in the Fig. 9, the two pixel by two pixel region encompassed by the interpolation filter includes two saturated pixel values, which are not taken into account by the interpolation process. As a result, an interpolated pixel 129 is obtained at the center of the two pixel by two pixel region having a value which is the average of two non-saturated and non-blackened pixel values in the region. Alternatively, saturated and blackened pixels may be assigned respective predefined values and are included in the interpolation computation.

Advantageously, each pixel value is weighted in accordance its contribution in increasing the quality of the interpolated result. Because the four neighboring pixels are normalized by different exposure values, the signal-to-noise ratio (SNR) of each of the four pixels differs from each other. By weighting each pixel value with the SNR, the interpolation is made more immune to noise. Given the response function  $f(M)$  of pixel value  $M$ , the SNR of the pixel value can be computed as  $SNR(M) = f(M)/f'(M)$ , where  $f'(M)$  is the first derivative of  $f(M)$ .

The interpolation process carried by the interpolator 11 of the image sensor 4 is further illustrated in Figs. 10A and 10B. Referring to Fig. 10A, there is shown an original image grid 150 defined by spaced intersecting perpendicular lines extending in a vertical direction (the  $y$  direction) and in a horizontal direction (the  $x$  direction). The image sensor 3 comprises an array of light-sensing elements 151 disposed at respective intersections (pixel position) of the original image grid 150. The image sensor 3 providing a respective pixel value corresponding to each of the light-sensing elements when exposed to incident light. Overlapping the original image grid 150 is an interpolation grid 152 also defined by spaced intersecting perpendicular lines extending in the vertical direction and in the horizontal direction. Referring now to Fig. 10B, the interpolation filter 153 encompasses each different four intersection regions of the original image grid 150 to derive interpolated pixel values 154 at respective intersections of the interpolation grid. In the present exemplary embodiment, the interpolation grid is identical to the original image grid and is displaced from one another by a one-half grid position in the horizontal direction and a one-half grid position in the vertical position. It will be understood by those skilled in the art that the interpolation grid need not be identical to the original image grid and that interpolation filters other than a two pixel by two pixel averaging filter may be used,



such as a bi-linear interpolation filter, a bi-cubic interpolation filter, a B-spline interpolation filter, a Gaussian interpolation filter or any other interpolation filter known to those skilled in the art. Moreover, it is noted that the disposition of the light-sensing elements need not be at intersections of a grid but may be any form of array.

Referring now to Fig. 11, there is shown a flow diagram 300 representing the processing which is carried out by the image processor 4. First, the process of loop 201 is repeated for each pixel location, where  $x$  and  $y$  are the  $x,y$  coordinates of the pixel location and  $xSize$  and  $ySize$  are the  $x$  dimension and the  $y$  dimension of the pixel array. Loop 201 includes steps 202, 203, 204, 205, 206, 207, 208 and 209. In step 202, pixel value  $M(x,y)$  at pixel location  $(x,y)$  is evaluated. If  $M(x,y)$  is smaller than  $noiseLevel$ , which is a predefined small pixel value, then step 203 is carried out. If  $M(x,y)$  is not smaller than  $noiseLevel$ , then step 205 is performed. In step 203, the exposure value  $E(x,y)$  corresponding to the pixel location is read from exposure pattern memory 5. If  $E(x,y)$  is the highest exposure value, then step 205 is performed. Otherwise, step 204 is carried out. In step 204, the pixel is marked as having a “blackened” pixel value and the current iteration of the loop terminates. The marking is done by writing a special value into the pixel location in temporary memory. In step 205, pixel value  $M(x,y)$  is evaluated. If  $M(x,y)$  is larger than  $saturationLevel$ , which is a predefined very large pixel value, then step 206 is carried out. If  $M(x,y)$  is not larger than  $saturationLevel$ , then steps 208 and 209 are carried out. In step 206, the exposure value  $E(x,y)$  is read from memory 5. If  $E(x,y)$  is the lowest exposure value, then steps 208 and 209 are performed. Otherwise step 207 is carried out. In step 207, the pixel is marked as a “saturated” pixel value in temporary memory, and the current iteration of loop 201 is terminated. In step 208,  $M(x,y)$  is calibrated in a manner described in connection with Figs. 6, 7 and 8.

In step 209,  $M(x,y)$  is normalized as described in connection with Figs. 6, 7 and 8, and the current iteration of loop 201 is terminated.

Turning to Fig. 11A, there is shown a flow diagram of the details of the calibration step 208 of the flow diagram of Fig. 11, as carried out by the calibrator 9. In step 311, the pixel value  $M(x,y)$  at each pixel position  $(x,y)$  is provided as an input  $M$ . In step 312, the response function  $f$  is applied to  $M$  to obtain  $m$ . As described above, the response function can be in the form of a look-up table, a parametric form or other appropriate data form. Assuming that the response function data is in the form of look-up table with 256 levels,  $M$  is normalized and digitized into an index value indicating one of the 256 levels. The look-up table is then used to find  $f(M)$  with the index value corresponding to  $M$ . In step 313,  $M$  is provided as an output, which in the flow diagram of Fig. 11 is the pixel value  $M(x,y)$  provided to step 209.

Returning to Fig. 11, after loop 201 is completed for all pixel positions, loop 210 is processed. Loop 210 is repeated for each pixel position from location (1,1) to location  $(xSize - 1, ySize - 1)$ . In loop 210, step 211, loop 212, steps 213, 214 and 215 are carried out. In step 211,  $L(x,y)$  and  $N$  are both initialized to zero. Here,  $L(x,y)$  indicates the radiance value at position  $(x,y)$  in the output image memory 7 and  $N$  indicates the number of pixels processed. Then the process of loop 212 is repeated with  $(i,j)$ . Both,  $i$  and  $j$  vary from 0 to 1. In loop 212, steps 213 and 214 are carried out. In step 213, the marking of pixel  $(x+i,y+j)$  is determined. If the pixel is not marked, then step 214 is performed. Otherwise, the current iteration of the loop terminates. In step 214, weight value  $W$  is calculated as the SNR of pixel value  $M(x+i,y+j)$ . Then pixel value  $M(x+i,y+j)$  is multiplied by  $W$  and the product is added to  $L(x,y)$ , and  $W$  is added to  $N$ . After loop 212 is finished, step 215 is carried out. In step 215,

$L(x,y)$  is divided by  $N$ , after the which the loop terminates. After the loop 210 is completed for all pixel locations, the processing by the image processor 4 is completed.

Referring again to Fig. 1, the imaging system according to the first exemplary embodiment of the present invention may be modified by eliminating the mask 101 and using an image sensor 3 comprising an array of light-sensing elements (pixels) having a spatially varying pattern of photosensitivities. The photosensitivity pattern of the light-sensing elements are stored as respective sensitivity values in memory 5 in place of the exposure pattern. A respective response function for each pixel is stored in memory 6 in place of the single response function for the image sensor. Turning again to Fig. 3, the calibrator 9 receives pixel values of the captured image 8 and uses the respective response functions in memory 6 to linearize the pixel values. The linearized pixel values are then normalized by the normalizer 10 using the photosensitivity values stored in memory 5. The normalized pixel values are then interpolated in the manner described to derive the high dynamic range image pixel values.

Turning now to Fig. 12, there is shown a functional block diagram 400 of an imaging system according to a second exemplary embodiment of the present invention. The system according to the second exemplary embodiment comprises a variable mask 12, a mask controller 13, an image sensor 3, an exposure pattern memory 5, a response function memory 6, an output image memory 7, an image processor 14, and a monitor image memory 15. Like the system of Fig. 1, incident light from a scene passes through a mask 12 having a spatially varying transparency pattern before impinging on the light sensitive surface of an image sensor 3 which provides corresponding pixel values to an image processor 14. The image processor 14 also receives response function data from the response function memory 6 and exposure values from an exposure pattern memory 5 and provides high dynamic range image data to

an output image memory 7. However, unlike the system of Fig. 1, the system 400 of Fig. 12 employs a mask 12 having a transparency pattern that may be varied by the application of exposure control signals thereto, and a mask controller 13 that responds to the pixel values provided by the image sensor 3 for generating the exposure control signals applied to the mask 12 and corresponding exposure values provided to the exposure pattern memory 5. In addition, the image processor 14 provides monitor image data to be stored in the monitor image memory 15. The monitor image data have a compressed dynamic range with image detail preservation for display by a low dynamic range display device, such as a television, a video monitor or a computer display. The mask controller 13 receives the output of the image sensor 3, and adjusts the spatially varying transparency of the mask 12 such that saturated and blackened pixel values are minimized.

Turning now to Fig. 13, there is shown a block diagram of 500 of the hardware components of a video camera implementation of the system of Fig. 12. The video camera implementation comprises an optical attachment 161 having a first lens component 162 for focusing a scene onto the variable mask 12 and a second lens component 163 for focusing the image of the scene after passing through the mask 12 and a light diffuser 131 onto the light sensing surface of a CCD light-sensing array 165. The optical attachment 161 also includes a liquid crystal mask controller 183 for applying mask control signals to the liquid crystal mask 12 for varying its transparency pattern. The block diagram 500 also includes an image sensing part 164 having a CCD light-sensing array 165 and a preamplifier 166 for adjusting the amplitude of the CCD output and for reducing noise. The preamplifier 166 includes several analog circuits which are usually implemented in a video camera, such as a correlated double circuit (a noise reduction circuit), an automatic gain control circuit, a gamma correction circuit and a knee circuit. The

output of the preamplifier 166 is provided to an analog-to-digital converter 169 in the image processing part 167. The analog-to-digital converter 169 digitizes the captured images. The actual computing of the image processor 14 of Fig. 12 is carried out by the processing unit 168, which has access to a RAM 170, a ROM 171, a Frame Memory 1 172, a Frame Memory 2 178, and a Frame Memory 3 174. In the video camera implementation 500 of Fig. 13, a liquid crystal mask controller 183 provides the controlling voltage to the liquid crystal mask 12. The controlling voltages applied to the liquid crystal mask are computed by the Processing Unit 168. The ROM 171 provides storage for instructions executed by the Processing Unit 168, as well as control parameters. The RAM 170 provides temporary data storage during processing. Frame Memory 1 172 corresponds to the output image memory 7 of Fig. 12, Frame Memory 2 173 corresponds to the Exposure Pattern Memory 5 in Fig. 12, and Frame Memory 3 174 corresponds to the Monitor Image Memory 15 of Fig. 12. The high dynamic range image data stored in Frame Memory 1 172 is converted to an analog signal by a digital-to-analog converter 175 before being provided to Video Output Part 1 177, where the analog signals undergo processing by a Video Signal Processor 178, the output of which is provided to Output Unit 179, which provides a video output 181 of the high dynamic range image. The monitor image data in Frame Memory 3 174 is converted to an analog signal by digital-to-analog converter 176. The analog signal for the monitor image is provided to Video Output Part 2 180 where in undergoes processing by Video Signal Processor 181, the output of which is provided to Output Unit 182, which provides the video output 182 of the monitor image. It is noted that while Video Output Part 1 177 and Video Output Part 2 180 are part of the video camera implementation, these components have no counterparts in the basic imaging system diagram of Fig. 12.

Turning now to Fig. 14, there is illustrated an exemplary structure of the image capture components 600 which may be used in the first and second exemplary embodiments of the present invention. A fixed pattern or liquid crystal mask 130 and a light diffuser 131 are positioned parallel to the image plane of a CCD light-sensing array 165, which is embedded in a camera body 134. The mask 130 and a light diffuser 131 are disposed between two optical components 132 and 133. The incident light from a scene is focused onto the mask 130 by the first optical component 132. Light attenuated by the mask 130 and passed through the light diffuser 131 is focused onto the image plane of the CCD light-sensing array 165 by the second optical component 133. In this manner, the light measured by the CCD light-sensing array 165 is in focus with respect to the mask 130 and the scene. It is noted that the light impinging on a pixel position R of the CCD image sensing device 165 comes only from a small area Q of the mask 130 through which the light has passed. The light diffuser 131 positioned directly behind the mask 130 removes directionality of focused light. Alternatively, the light diffuser 131 may be positioned directly in front of the mask 130 or two separated light diffusers may be positioned one directly in front and one directly behind the mask 130. The small area Q in turn receives light only from a single point P of the scene that is being imaged. Although a liquid crystal array is the preferred variable exposure mask for the second exemplary embodiment of the invention, other devices, such as an array of electro-optic light modulators, where the exposure pattern can be controlled by the application of appropriate signals may also be used.

As mentioned above, it is preferred that the variable mask 12 be a two-dimensional array of liquid crystal cells having transparencies that are individually controllable by the application of respective exposure control voltage signals. As shown in Fig. 15, each cell of the variable mask 12

controls the transmission of light to a respective one or more of the pixels of the light-sensing element array 165 of the image sensor 3, where each of the light-sensing elements of the array 165 corresponds to a respective pixel. For example, the  $4 \times 4$  pixel area which is indicated by the dotted square 183 in the light-sensing element array 165 receives only light that has passed through the mask cell 184 of the variable mask 12. The exposure control signals that control the transparency (attenuation) of each cell of the variable mask 12 are provided by a mask controller 13 which receives the output (pixel values) of the image sensor 3 and computes the exposure control signals for the cells of the mask according to the received pixel values. The exposure control signal for each cell is computed so as to (1) minimize the number of saturated or blackened pixels within the corresponding area 183 of the light-sensing element array 165, (2) maximize the signal-to-noise ratio of the average pixel value provided by the image sensor 3, and (3) maximize the spatial smoothness of the exposure values of the mask cell array 12.

Turning now to Fig. 16, there is illustrated an example of the evolution of the exposure pattern of the variable mask 12 under the control of the mask controller 13. In this figure, time shifts from left to right. The illustrations 137 at the top row of the figure represent the radiance from the scene, which in the present example remains constant over time. The illustrations 138, 139 and 140 in the center row of the figure represent the temporal change of the exposure pattern of the mask 12. The illustrations 141, 142 and 143 in the bottom row of the figure depict the temporal change of the captured image as represented by the output of the image sensor 3. In the initial state (left column), the exposure pattern 138 starts out with the same transparency (attenuation) for all of the cells of the variable mask 12. Thus, the radiance of the scene 137, which has a very bright object 185 and a very dark object 186, are equally attenuated to produce the initial captured (un-normalized) image 141. However, since the dynamic

range of the image sensor 3 is low relative to the range of radiance of the scene, the initial captured image 141 does not include all of the visual details of the radiance scene 137. In the initial captured image 141, the dark object 187 is almost fully blackened and the bright object 188 is almost fully saturated. After the mask controller 13 has adjusted the exposure values of every cell of the variable mask 12 to satisfy the three criteria mentioned above, the second exposure pattern 139 results from the mask controller 13 applying new exposure control signals to the variable mask 12. In the exposure pattern 139, the exposure values of the bright object areas are decreased, the exposure values at the dark object areas are increased and the exposure values at the background areas are slightly increased. The image 142 captured using the exposure pattern 139 has no saturated or blackened pixels, and hence the details of the image are enhanced. In a like manner, the mask controller 13 continues to adjust the exposure values to obtain exposure pattern 140 which has improved smoothness. The image 143 obtained with the exposure pattern 140 shows improved image detail as a result of the improved the smoothness of the exposure pattern. It is noted that the process of adapting the exposure pattern by the exposure controller 13 is particularly suited to temporally varying scenes, such as scenes with moving objects.

Referring now to Fig. 17, there is shown a flow diagram 700 of the processing carried out by the mask controller 13. The flow diagram 700 represents the process for computing an exposure control signal for one cell of the variable mask 12, and must therefore be repeated for each cell of the mask. In step 216,  $S_1$  and  $S_2$  are both initialized to zero. Here,  $S_1$  indicates the exposure control value for satisfying the first criterion of minimizing the number of saturated or blackened pixel values within the area of the light-sensing element array that receives light from the mask cell, and  $S_2$  indicates the



exposure control value that satisfies the second criterion of maximizing the signal-to-noise ratio of the average pixel value provided by the image sensor 3. The process of loop 217 is repeated for each pixel within the area of the light-sensing element array 165 that receives light which has passed through the cell of the variable mask 12. Here,  $Q$  is the number of pixels within that area. The loop 217 includes steps 218, 219, 220, 221 and 222. In step 218, the pixel value  $M_q$  is evaluated. If  $M_q$  is smaller than noiseLevel, which is a predefined very small pixel value, then step 219 is carried out. Otherwise, step 222 is performed. In step 219,  $S_1$  is incremented and the current iteration of loop 217 terminates. In step 220, pixel value  $M_q$  is evaluated. If  $M_q$  is larger than saturationLevel, which is a predefined very large pixel value, then step 221 is carried out. Otherwise, step 222 is performed. In step 221,  $S_1$  is decremented, and the current iteration of the loop terminates. In step 222,  $S_2$  is updated by adding the quantity  $(M_{\text{best}} - M_q)$ , where  $M_{\text{best}}$  is a predefined pixel value which has the best signal-to-noise ratio for the image sensor 3 being used. After loop 217 is finished, steps 223 and 224 are carried out. In step 223,  $S_3$  is computed by using the equation shown in block 223. In this equation,  $g_k$  are weight values of a low pass kernel,  $E_k$  are exposure values of the neighbor cells, and  $E$  is the exposure value of the currently processed cell. This computation provides a type of low pass filtering, which is commonly called "unsharp masking." In step 224, the exposure value  $E$  of the currently processed cell is updated by a weighted summation of  $S_1$ ,  $S_2$  and  $S_3$ , where the weights  $w_1$ ,  $w_2$  and  $w_3$  are predefined balancing factors experimentally determined to optimize the image quality. After step 224 is finished, the processing for the currently processed cell is completed.

Turning now to Fig. 18, there is shown a data flow diagram 800 of the image processor 14 of the system of Fig. 12. The image processor 14 comprises a calibrator 9, a normalizer 10, a smoother 16 and

an exposure reapplicator 17. As with the image processor 4 of the first exemplary embodiment of the present invention illustrated in Fig. 1, the calibrator 9 calibrates the pixel values of an image captured by image sensor 3 into a linear response image by using the response function data stored in the response function memory 6. Then the normalizer 10 converts the linear response image into an image which is proportional to the scene radiance. It is noted that the image processor 14 of the second embodiment of the present invention does not require interpolation of the output of the normalizer 10 because the exposure of the variable mask 12 is adjusted by the mask controller 13 to minimize saturated and blackened pixel values.

Furthermore, the image processor 14 produces monitor image pixel values to be written into the monitor image memory 15. To produce the monitor image pixel values, smoother 16 smooths the exposure values from the exposure pattern memory 5. Then the exposure reapplicator 17 applies the smoothed exposure values to the pixel values of the high dynamic range image as produced by the normalizer 10. Fig. 20 illustrates the process for deriving the monitor image pixel values. The left hand column of Fig. 19 is the same as the right hand column of Fig. 16. Because after exposure control the captured image 143 still has slight discontinuities caused by the boundaries of the mask cells, it is not ideally suited for display purposes. Therefore, the smoother 16 smooths the exposure pattern 140 to derive the smoothed exposure pattern 145, which has no visible discontinuities. The monitor image 146 is then obtained by reapplying the smoothed exposure pattern 145 to the high dynamic range image 144, which has already been obtained from exposure pattern 140 and the captured (un-normalized) image 143. The monitor image 146 is better suited for display purposes than the captured image 143 or the high dynamic range image 144 because the monitor image 146 has no discontinuities and has a dynamic

range similar to that of the image sensor 3. The monitor image may also serve as video output for subsequent processing

Referring to Fig. 20, there is shown a flow diagram 900 of the processing carried out by the smoother 16 and the exposure reapplicator 17. With respect to smoothing, loop 301 is carried out N times, where N is a predetermined number, usually in the range from 1 to 5. In loop 301, step 302, loop 303, step 304 and step 305 are carried out. In step 302 exposure pattern data E in the exposure pattern memory 5 is copied to another memory space of the same size and is referred to as  $E_s$ . In the example of Fig. 20, the exposure pattern has the same dimensions as the image so that each pixel of the image has the same coordinates as its corresponding exposure value. The loop 303 is repeated for each pixel position of  $E_{temp}$ , which is a temporary exposure pattern data storage of the same size as E and  $E_s$ . In loop 303, step 304 is processed. In step 304, a smoothing filter g is applied to the current position (x,y) of  $E_s$ . The filtering computation is expressed in the box of step 304. The smoothing filter  $g(u,v)$  may be that shown in Fig. 21. Referring to Fig. 21, there is shown a  $5 \times 5$  (k=5) Gaussian blur filter. Each number in the grid 501 expresses the filter coefficient at that position of the filter. For example,  $g(3,3) = 0.16$ . Referring again to Fig. 20, the computed value in step 304 is stored in the same position (x,y) of  $E_{temp}$ . After loop 303 is finished, step 305 is carried out. In step 305, the smoothed exposure values in  $E_{temp}$  are copied to  $E_s$ . After loop 301 has been repeated N times, loop 306 is carried out to implement exposure reapplication. The loop 306 is repeated for each pixel position of  $E_s$ . In loop 306, step 307 is carried out. In step 307, the pixel value  $L(x,y)$  in the output image memory 7 and the exposure value  $E_s(x,y)$  are multiplied and the product of the multiplication is stored in the same pixel position of the monitor image memory 15 as  $L_{monitor}(x,y)$ . When loop 306 is completed, processing for

smoothing of the exposure pattern and for reapplication of the smoothed exposure of pattern to the high dynamic range image ends.

Turning now to Fig. 22, there is shown a functional diagram of a system 1000 for capturing high dynamic range images of a scene according to a third exemplary embodiment of the present invention.

5 The system includes a photographic film camera 509 for exposing a masked image of a scene onto photographic film. As mentioned above, the masked image may be obtained by providing a mask 101 having a spatially varying transparency pattern, such as that shown in Fig. 4A, between the shutter 504 of the camera and the plane of the film 505. Alternatively, the mask may be attached to each frame of film or the film emulsion may have a spatially varying pattern of exposure sensitivity. In each case, the exposure value for each region of the film has been previously determined and is stored in an exposure pattern memory 5. After being exposed with a masked image, the film is processed to produce either a transparency or a print containing the masked image. The film or print containing the masked image is then scanned by a scanner 507 which provides pixel values representative of the masked image. The pixel values are provided to an image processor 4 which may be identical to the image processor of the system of Fig. 1 and may have a data flow diagram identical to the one shown in Fig. 3. The combined response function of the film and the scanner are stored in a response function memory 6 to be used by the image processor 4 for calibration purposes. Instead of receiving exposure values directly from the exposure pattern memory 5, the system 1000 of Fig. 22 includes an aligner which receives the output of the scanner 507 and the exposure values stored in exposure pattern memory 5, and provides alignment corrected exposure values to the image processor for normalization purposes. The image processor 4 provides a high dynamic range output image to an output image memory 7. In typical film cameras, the

film is moved frame by frame with each frame being positioned behind the shutter 504. This movement of the film causes some misalignment between the currently exposed frame of the film 505 and the mask 101. The aligner 508 is used to correct for such misalignment.

Turning now to Fig. 23, there is shown a data flow diagram 1100 of the aligner 508 in Fig. 22.

5 The aligner 1100 has three fast Fourier transform processors 512, 513 and 514, a rotation detector 515, a shift detector 516, a rotator 517 and a shifter 518. The process carried out by the aligner 508 is represented by the flow diagram in Fig. 24. Referring to Fig. 24, in step 519 the Fourier transform  $I(u,v)$  of the image  $I(x,y)$  is computed by FFT1 512. In step 520, the Fourier transform  $E(u,v)$  of the exposure pattern  $E(x,y)$  is computed by FFT2 513. In step 521, the positions of the peaks of the magnitude of  $I(u,v)$  are detected. In step 522, the positions of the peaks of the magnitude of  $E(u,v)$  are detected. In step 523, a  $2 \times 2$  rotation matrix  $M$  is estimated by least square optimization with the error function which is shown in block 523. Steps 521, 522 and 523 are all carried out by the rotation detector 515 in Fig. 23. In step 524, a rotated exposure pattern  $E_{\text{rotated}}(x,y)$  is computed by rotating the exposure pattern  $E(x,y)$  with the rotation matrix  $M$ . Step 524 is carried out by the rotator 517 of Fig. 23. In step 525, a shift vector  $(s,t)$  is estimated by searching for the shift vector which minimizes the error function shown in box 525. Finally, in step 526 the corrected exposure pattern  $E_{\text{corrected}}(x,y)$  is computed by shifting  $E_{\text{rotated}}(x,y)$  by the shift vector  $(s,t)$ . The corrected exposure pattern  $E_{\text{corrected}}(x,y)$  is provided to a corrected exposure pattern memory 519 for use by the image processor 4 for normalization purposes.

While the present invention has been particularly described with reference to exemplary  
20 embodiments thereof, it will be understood by those skilled in the art that various modifications and alterations may be made without departing from the spirit and scope of the invention. Accordingly, the

disclosed embodiments of the invention are considered merely illustrative, and the invention is limited in scope only as specified in the appended claims.

continued on next page

## CLAIMS:

1                   1. A system for high dynamic range imaging comprising:  
2                   an image sensor comprising an array of light-sensing elements, the image sensor sensing  
3 an image of a scene and providing corresponding pixel values representing light intensities impinging on  
4 respective ones of the light-sensing elements, the image sensor providing a saturated pixel value when  
5 the intensity of light impinging on a corresponding one of the light-sensing elements is greater than a  
6 first threshold level and providing a blackened pixel value when the intensity of light impinging on a  
7 corresponding one of the light-sensing elements is below a second threshold level, the image sensor  
8 having a low dynamic range relative to the range of light intensities of the image of the scene;  
9                   a mask interposed between the scene and the array of light-sensing elements of the image  
10 sensor, the mask having a multiplicity of light-transmitting cells each controlling the exposure of a  
11 respective one or more of the light-sensing elements to light from the scene, each of the light-sensing  
12 elements having a corresponding exposure value indicative of the transparency of the cell through which  
13 light impinging on the light-sensing element passes;  
14                   a first memory storing exposure values corresponding to the light-sensing elements; and  
15                   an image processor coupled to the image sensor for receiving the pixel values provided  
16 thereby and coupled to the first memory for receiving the exposure values corresponding to the pixel  
17 values, the image processor comprising a normalizer for mapping the pixel values by a function of the  
18 exposure values to derive corresponding normalized pixel values.

1                   2. The system according to claim 1, wherein the normalizer divides each of the pixel  
2 values with the exposure value corresponding to the light-sensing element receiving light intensity  
3 represented by the pixel value to derive corresponding normalized pixel values.

1                   3. The system according to claim 1, wherein the exposure values corresponding to the  
2 light-sensing elements are fixed and the image processor further comprises an interpolator for  
3 interpolating the normalized pixel values to derive interpolated pixel values at respective positions of a  
4 second array overlapping the array of the light-sensing elements.

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1                   4. The system according to claim 3, wherein the interpolator of the image processor  
2 interpolates the normalized pixel values, excluding normalized pixel values corresponding to saturated  
3 pixel values or blackened pixel values.

1                   5. The system according to claim 3, wherein the interpolator of the image processor  
2 interpolates the normalized pixel values multiplied by respective weighting values.

1                   6. The system according to claim 5, wherein the weighting values are respective signal-  
2 to-noise ratios of the corresponding pixel values.

1                   7. The system according to claim 3, wherein the interpolator of the image processor  
2 applies an interpolation filter to the normalized pixel values.



1           8. The system according to claim 3, wherein the light-sensing elements of the array are  
2 disposed at respective intersections of a first grid defined by spaced intersecting perpendicular lines  
3 extending in a vertical direction and a horizontal direction, and the interpolator derives interpolated pixel  
4 values at respective intersections of a second grid defined by spaced intersecting perpendicular lines  
5 extending in the vertical direction and in the horizontal direction, the first and second grids overlapping  
6 one another.

9. The system according to claim 8, wherein the interpolator of the image processor  
separately interpolates normalized pixel values in each different region of the first grid, each region  
overlapping adjacent regions and encompassing a predetermined number of intersections of the first  
grid.

10. The system according to claim 9, wherein the mask comprises repetitively disposed  
identical groups of cells having different transparencies.

1           11. The system according to claim 10, wherein each of the repetitively disposed identical  
2 groups of cells of the mask consists of four neighboring cells having different transparencies, each cell  
3 controlling the light exposure of a different one of the light-sensing elements, and the first and second  
4 grids have identical dimensions and are displaced from one another by one-half grid position in the  
5 horizontal direction and one-half grid position in the vertical direction.

1                   12. The system according to claim 9, wherein the interpolator of the image processor  
2 derives a respective interpolated pixel value in each different region of the first grid by taking the  
3 average of all normalized pixel values in the region which do not correspond to a saturated pixel value or  
4 a blackened pixel value.

1                   13. The system according to claim 1 further comprising a second memory storing a  
2 response function of the image sensor, wherein the image processor is coupled to the second memory for  
3 receiving the response function and further comprises a calibrator for converting the pixel values  
4 provided by the image sensor to linear response pixel values in accordance with the response function  
5 before the pixel values are normalized by the normalizer.

1                   14. The system according to claim 3 further comprising an output image memory  
2 coupled to the image processor for receiving and storing the interpolated pixel values.

1                   15. The system according to claim 1 further comprising a first lens system located  
2 between the scene and the mask for projecting an image of the scene onto the mask and a second lens  
3 system for projecting the image of the scene as transmitted through the mask onto the array of light-  
4 sensing elements.

1                   16. The system according to claim 15, further comprising a light diffuser adjacent to the  
2 mask for removing directionality of light focused by the first lens system.

1                   17. The system according to claim 1, wherein the array of light sensing elements is a  
2 solid state device image sensing device.

1                   18. The system according to claim 17, wherein the solid state device is a charge-coupled  
2 device light sensing array.

1                   19. The system according to claim 18, wherein the solid state device is a CMOS light-  
2 sensing array.

1                   20. The system according to claim 17, wherein the mask is integrated with the light-  
2 sensing elements on the same substrate.

1                   21. The system according to claim 1, wherein the mask is made of a nonlinear optical  
2 material.

1                   22. A system for high dynamic range imaging comprising:  
2 an image sensor comprising an array of light-sensing elements, the image sensor sensing  
3 an image of a scene and providing corresponding pixel values representing light intensities impinging on

4        respective ones of the light-sensing elements, the image sensor providing a saturated pixel value when  
5        the intensity of light impinging on a corresponding one of the light-sensing elements is greater than a  
6        first threshold level and providing a blackened pixel value when the intensity of light impinging on a  
7        corresponding one of the light-sensing elements is below a second threshold level, the image sensor  
8        having a low dynamic range relative to the range of intensities of the image of the scene;

9                a mask interposed between the scene and the array of light-sensing elements of the image  
10        sensor, the mask having a multiplicity of light-transmitting cells each controlling the exposure of a  
11        respective one or more of the light-sensing elements to the light from the scene, each of the light-sensing  
12        elements having a corresponding exposure value indicative of the transparency of the cells through  
13        which light impinging on the light-sensing element passes, the exposure value of each of the cells of the  
14        mask being alterable by applying a respective exposure control signal to the mask;

15                a mask controller coupled to the image sensor for receiving the pixel values provided  
16        thereby and for computing, and applying to the mask, exposure control signals for minimizing the  
17        number of saturated pixel values and blackened pixel values from the image sensor, and providing  
18        exposure values corresponding to the applied exposure control signals; and

19                an image processor coupled to the image sensor for receiving the pixel values provided  
20        thereby, the image sensor comprising a normalizer for mapping the pixel values by a function of the  
21        exposure values to derive corresponding normalized pixel values.

1           23. The system according to claim 22, wherein the normalizer of the image processor  
2 divides each of the pixel values by the exposure value corresponding to the light-sensing element  
3 receiving light intensity represented by the pixel value to derive corresponding normalized pixel values.

1           24. The system according to claim 22, further comprising an exposure pattern memory  
2 coupled to the mask controller for receiving and storing the exposure values, and wherein the image  
3 processor is coupled to the exposure pattern memory for receiving the exposure values corresponding to  
4 the pixel values from the image sensor.

25. The system according to claim 22 further comprising an output image memory  
coupled to the normalizer of the image processor for receiving and storing the normalized pixel values.

26. The system according to claim 24 further comprising:  
a smoother coupled to the exposure pattern memory for receiving exposure values stored  
therein and applying a smoothing filter to the exposure values to derive smoothed exposure values  
4 corresponding to the normalized pixel values;

5 an exposure reapplicator coupled to the normalizer of the image processor for receiving  
6 the normalized pixel values and for multiplying each of the normalized pixel values with a  
7 corresponding smoothed exposure value to derive monitor image pixel values; and

8 a monitor image generator coupled to the exposure reapplicator for providing the monitor  
9 image pixel values.

1                   27. The system according to claim 22, wherein the mask controller computes the  
2 exposure control signals to maximize the signal-to-noise ratio of the average pixel value provided by the  
3 image sensor.

1                   28. The system according to claim 22, wherein the mask controller computes the  
2 exposure control signals to maximize the spatial smoothness of the exposure values corresponding to the  
3 light-sensing elements of the image sensor.

29. The system according to claim 22, wherein the mask comprises a liquid crystal array.

30. The system according to claim 22 further comprising a first lens system located  
between the scene and the mask for projecting an image of the scene onto the mask and a second lens  
system for projecting the image of the scene as transmitted through the mask onto the array of light-  
sensing elements.

1                   31. The system according to claim 30 further comprising a light diffuser adjacent the  
2 mask for removing directionality of light focused onto the mask.

1                   32. The system according to claim 22, wherein the array of light-sensing elements is a  
2 solid state image sensing device.

1 33. The system according to claim 32, wherein the solid state image sensing device is a  
2 charge coupled device light-sensing array.

1 34. The system according to claim 32, wherein the solid state image sensing device is a  
2 CMOS light-sensing array.

1 35. A system for high dynamic range imaging comprising:  
2 an image sensor comprising an array of light-sensing elements, the image sensor sensing  
3 an image of a scene and providing corresponding pixel values representing light intensities impinging on  
4 respective ones of the light-sensing elements, each light-sensing element having a respective first  
5 threshold level so as to cause the image sensor to provide a saturated pixel value when the intensity of  
6 light impinging on the light-sensing element is greater than the respective first threshold level, each  
7 light-sensing element having a respective second threshold value so as to cause the image sensor to  
8 provide a blackened pixel value when the intensity of light impinging on the light-sensing element is  
9 below the respective second threshold level, the image sensor having a low dynamic range relative to the  
10 range of light intensities of the image of the scene, the light-sensing elements having respective spatially  
11 varying photosensitivities to incident light and corresponding photosensitivity values indicative of the  
12 respective photosensitivities  
13 a first memory storing photosensitivity values corresponding to each of the light-sensing  
14 element; and

15 an image processor coupled to the array of light-sensing elements for receiving the pixel  
16 values provided by the image sensor and coupled to the first memory for receiving the photosensitivity  
17 values corresponding to the light-sensing elements, the image processor comprising a normalizer for  
18 mapping the pixel values by a function of the photosensitivity values to derive corresponding  
19 normalized pixel values, and an interpolator for interpolating the normalized pixel values to derive  
20 interpolated pixel values at respective positions of a second array overlapping the array of light-sensing  
21 elements.

36. The system according to claim 35, wherein the normalizer of the image processor  
maps the pixel values by a function of the photosensitivity values by dividing each of the pixel values by  
the photosensitivity value corresponding to the light-sensing element receiving light intensity  
represented by the pixel value.

37. The system according to claim 35, wherein the light-sensing elements of the image  
sensor are disposed at respective intersections of a first grid defined by spaced intersecting perpendicular  
lines extending in a vertical direction and a horizontal direction, and the positions of the interpolated  
pixel values are respective intersections of a second grid defined by spaced intersecting lines extending  
in the vertical direction and in the horizontal direction.



1           38. The system according to claim 37, wherein the interpolator of the image processor  
2 separately interpolates normalized pixel values in each different region of the first grid, each region  
3 overlapping adjacent regions and encompassing a predetermined number of intersections of the first  
4 grid.

1           39. The system according to claim 37, wherein the array of light-sensing elements of the  
2 image sensor comprises repetitively disposed identical groups of light-sensing elements having different  
3 photosensitivities.

1           40. The system according to claim 39, wherein in each of the repetitively disposed  
2 identical groups of light-sensing elements consists of four neighboring light-sensing elements having  
3 different photosensitivities, and the first and second grids having identical dimensions and are displaced  
4 from one another by one-half grid position in the horizontal direction and one-half grid position in the  
5 vertical direction.

1           41. The system according to claim 38, wherein the interpolator of the image processor  
2 derives a respective interpolated pixel value in each different region of the first grid by taking the  
3 average of all normalized pixel values in the region which do not correspond to a saturated pixel value or  
4 a blackened pixel value.

1           42. The system according to claim 35, wherein the image sensor has a respective  
2 response function to light impinging on each of the light-sensing elements and the system further  
3 comprises a second memory storing the respective response functions of the image sensor, and wherein  
4 the image processor is coupled to the second memory for receiving the response functions and further  
5 comprises a calibrator for converting the pixel values provided by the image sensor to linear response  
6 pixel values in accordance with the respective response functions before the pixel values are normalized  
7 by the normalizer.

8           43. The system according to claim 35, further comprising an output image memory  
9 coupled to the image processor for receiving and storing the interpolated pixel values.

10          44. A method for high dynamic range imaging comprising the steps of:  
11 exposing an image sensor comprising an array of light-sensing elements to an image of a  
12 scene using a spatially varying exposure, the image sensor sensing the spatially varying exposure image  
13 and providing corresponding pixel values representing light intensities impinging on respective ones of  
14 the light-sensing elements, the image sensor providing a saturated pixel value when the intensity of light  
15 impinging on a corresponding one of the light-sensing elements is greater than a first threshold level and  
16 providing a blackened pixel value when the intensity of the light impinging on a corresponding one of  
17 the light-sensing elements is below a second threshold level, the image sensor having a low dynamic  
18 range relative to the range of light intensities of the image of the scene; and  
19

10 normalizing the pixel values provided by the image sensor with respect to the spatially  
11 varying exposure of the light-sensing elements to derive corresponding normalized pixel values.

1 45. The method according to claim 44, wherein the step of exposing the image sensor  
2 using a spatially varying exposure includes the step of using a mask having a multiplicity of light  
3 transmitting cells each controlling the exposure of a respective one or more of the light-sensing elements  
4 of the image sensor to light from the scene, each of the light-sensing element having a corresponding  
5 exposure value indicative of the transparency of the mask cell through which light impinging on the  
6 light-sensing element passes, and the step of normalizing the pixel values provided by the image sensor  
7 includes the step of mapping the pixel values by a function of the exposure values to derive  
8 corresponding normalized pixel values.

9 46. The method according to claim 45, wherein the step of mapping the pixel values by  
10 a function of the exposure values comprises dividing each of the pixel values with the exposure value  
11 corresponding to the light-sensing element receiving light intensity represented by the pixel value.

1 47. The method according to claim 44, wherein the exposure values corresponding to the  
2 light-sensing elements are fixed, and further comprising the step of interpolating the normalized pixel  
3 values to derive interpolated pixel values at respective positions of a second array overlapping the array  
4 of the light-sensing elements.

1           48. The method according to claim 44, wherein the step of interpolating the normalized  
2 pixel values include the step of applying an interpolation filter to the normalized pixel values.

1           49. The method according to claim 47, wherein the step of interpolating the normalized  
2 pixel values includes the steps of separately interpolating normalized pixel values in each different  
3 region of the array of the light-sensing elements, each region overlapping adjacent regions and  
4 encompassing a predetermined number of the light-sensing element positions.

50. The method of claim 49, wherein the steps of separately interpolating normalized  
pixel values in each different region of the array of light-sensing elements each include the step of taking  
the average of all normalized pixel values in the region, except for ones that correspond to a saturated  
pixel value or a blackened pixel value, to derive a respective one of the interpolated pixel values.

51. The method of claim 44 further comprising the step of calibrating the pixel values  
provided by the image sensor according to a response function of the image sensor to derive linear  
3 response pixel values before the step of normalizing the pixel values.

1           52. The method according to claim 47 further comprising the step of storing the  
2 interpolated pixel values in an output image memory.

1           53. The method of claim 45 further comprising the steps of projecting an image of the  
2 scene onto the mask, and projecting the image of the scene as transmitted through the mask onto the  
3 array of light-sensing elements.

1           54. The method of claim 53, wherein the step of projecting the image of the scene as  
2 transmitted through the mask onto the array of light-sensing elements includes projecting the image of  
3 the scene as transmitted through the mask and a light diffuser onto the array of light-sensing elements.

1           55. The method of claim 45, wherein the exposure value corresponding to each light-  
2 sensing element is alterable by applying a respective exposure control signal to the mask, and further  
3 comprising the steps of:

4           computing from the pixel values provided by the image sensor exposure control signals  
5 for minimizing the number of saturated pixel values and blackened pixel values from the image sensor;  
6           applying the computed exposure control signals to the mask; and  
7           providing exposure values corresponding to the applied exposure control signals for use  
8 in the normalizing step.

1           56. The method according to claim 55 further comprising the step of storing the  
2 normalized pixel values in an output image memory.

1 57. The method according to claim 55 further comprising the steps of:

2 smoothing the exposure values corresponding to the applied exposure control signals by  
3 applying a smoothing filter to the exposure values to derive smoothed exposure values corresponding to  
4 the normalized pixel values;

5 reapplying the smoothed exposure values to the normalized pixel values by multiplying  
6 each normalized pixel value with a corresponding smoothed exposure value to derive monitor image  
7 pixel values; and

8 storing the monitor image pixel values in a monitor image memory.

58. The method of claim 55, wherein the step of computing exposure control signals  
comprises computing exposure control signals to maximize the signal-to-noise ratio of the average pixel  
value provided by the image sensor.

59. The method according to claim 55, wherein the step of computing exposure control  
signals comprises computing exposure control signal to maximize the spatial smoothness of the  
corresponding exposure values.

1 60. A method for high dynamic range imaging comprising the steps of:

2 exposing a frame of photographic film to an image of a scene through a mask having a  
3 multiplicity of light transmitting cells controlling the exposures of respective regions of the film to light

4 from the scene, each of the respective regions of the film having a corresponding exposure value  
5 indicative of the transparency of the masked cell through which light impinging on the region passes;  
6 storing the exposure values corresponding to the respective regions of the film;  
7 processing the film to develop a masked image contained thereon or on a print thereof;  
8 scanning the processed film or a print thereof with an image scanner to derive pixel  
9 values corresponding to the respective regions of the film or a print thereof; and  
10 normalizing the pixel values from the scanner using the stored exposure values to derive  
11 normalized pixel values.

61. The method according to claim 60 further comprising the step of interpolating the  
normalized pixel values to derive interpolated pixel values.

62. The method according to claim 61 further comprising the step of storing the  
interpolated pixel values in an output image memory.

63. The method of claim 60 further comprising the step of aligning the pixel values  
corresponding to the respective regions of the film or a print thereof with the exposure values  
corresponding to the respective regions.

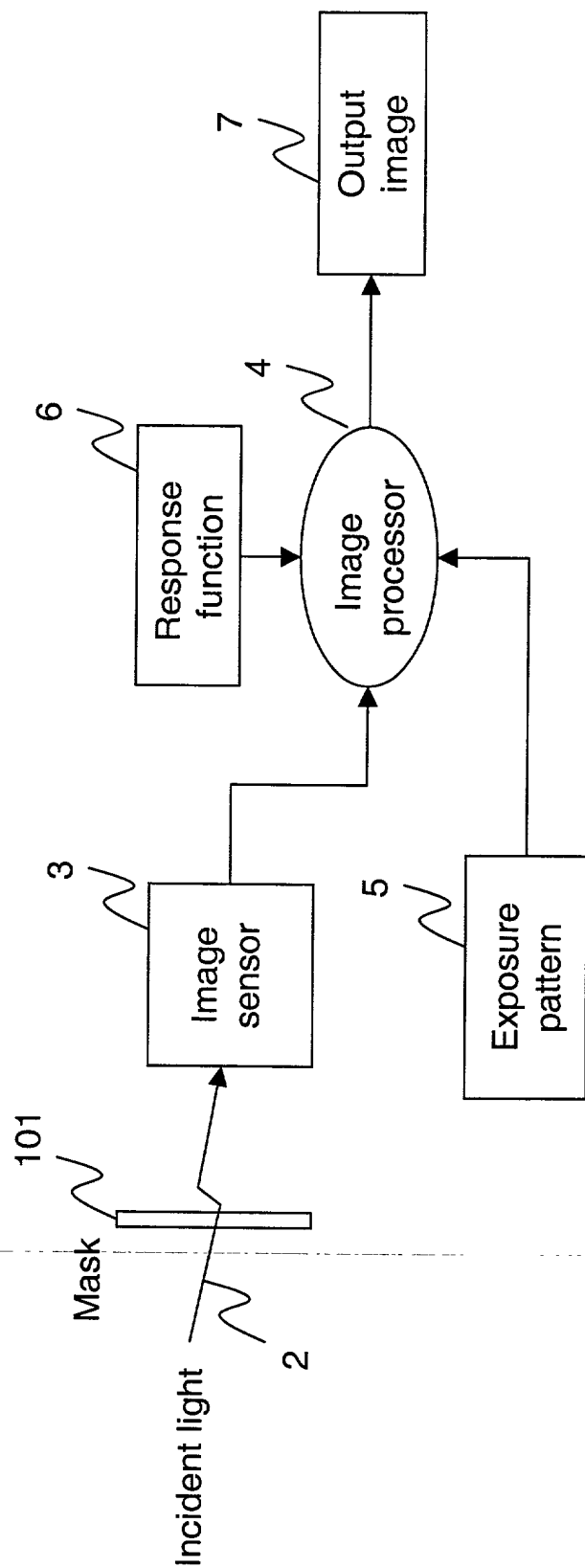
1                   64. The method according to claim 60 further comprising the step of calibrating the pixel  
2 values corresponding to the respective regions of the film or a print thereof in accordance with a  
3 response function of the film, the image scanner and a printer, if any, to derive linearized pixel values  
4 before the step of normalizing the pixel values.

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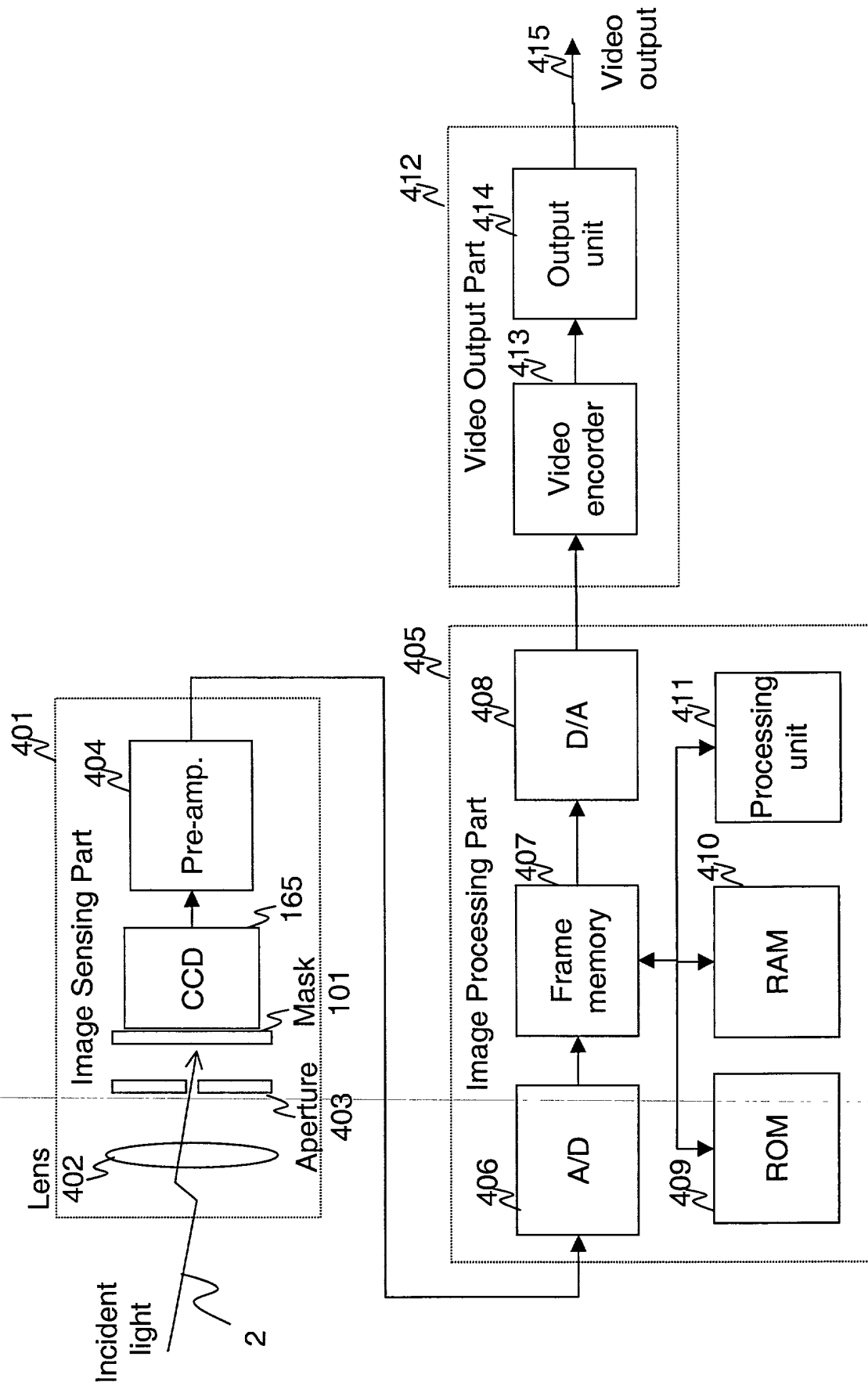
## ABSTRACT

The present invention provides apparatus and method for obtaining high dynamic range images using a low dynamic range image sensor. The image of a scene is captured with an image sensor using a spatially varying exposure function. The spatially varying exposure function can be implemented using  
5 as an optical mask with a fixed spatial attenuation pattern, or using a controllable attenuation cell array. The captured image after calibration to correct for nonlinear response of the image sensor, is then normalized with respect to the exposure function. Where the exposure function is a fixed spatial attenuation pattern, the normalized image is interpolated to account for pixels that are saturated or blackened. Where the exposure function is implemented using a controllable attenuation cell array, the exposure function is adjusted to minimize the number of saturated or blackened pixels within an area of pixel array exposed through a cell, to maximize the signal-to-noise ratio of the average pixel value, and to maximize the spatial smoothness of the exposure function. Also disclosed is a technique for detailed preserving dynamic range compression of a high dynamic range image for display on a low dynamic range display device. The technique entails applying a smoothing filter to the exposure function used to  
15 obtain the high dynamic range image, and then reapplying the smoothed exposure function to the high dynamic range image. Also disclosed is a method for obtaining high dynamic range images by exposing photographic film using a spatially varying exposure function. The exposed film is then developed and scanned to derive an electronic image which is aligned with the exposure function and processed in the same manner as images captured electronically using a fixed exposure function.

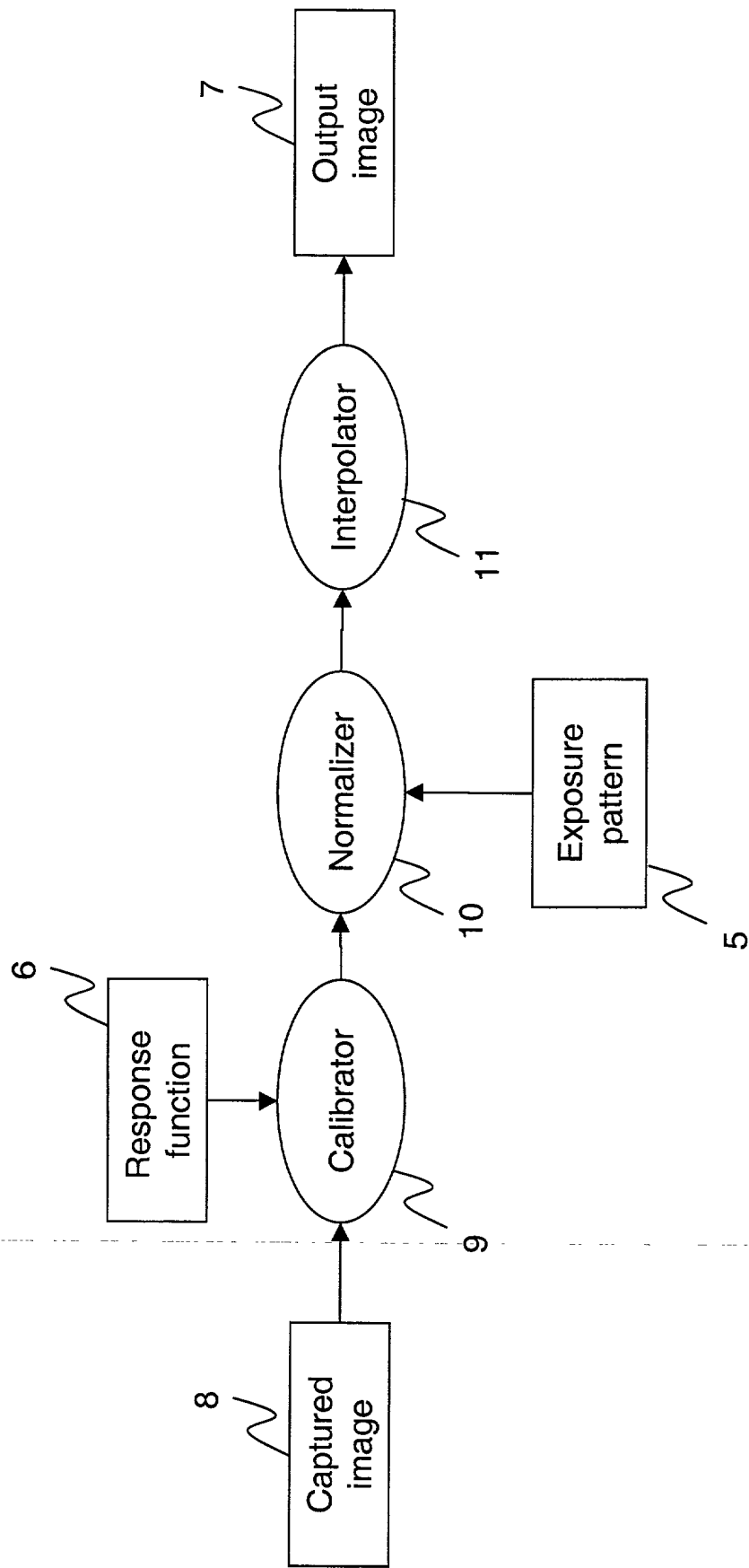


100

**Fig. 1**



200  
Fig. 2



3000  
Fig. 3

101

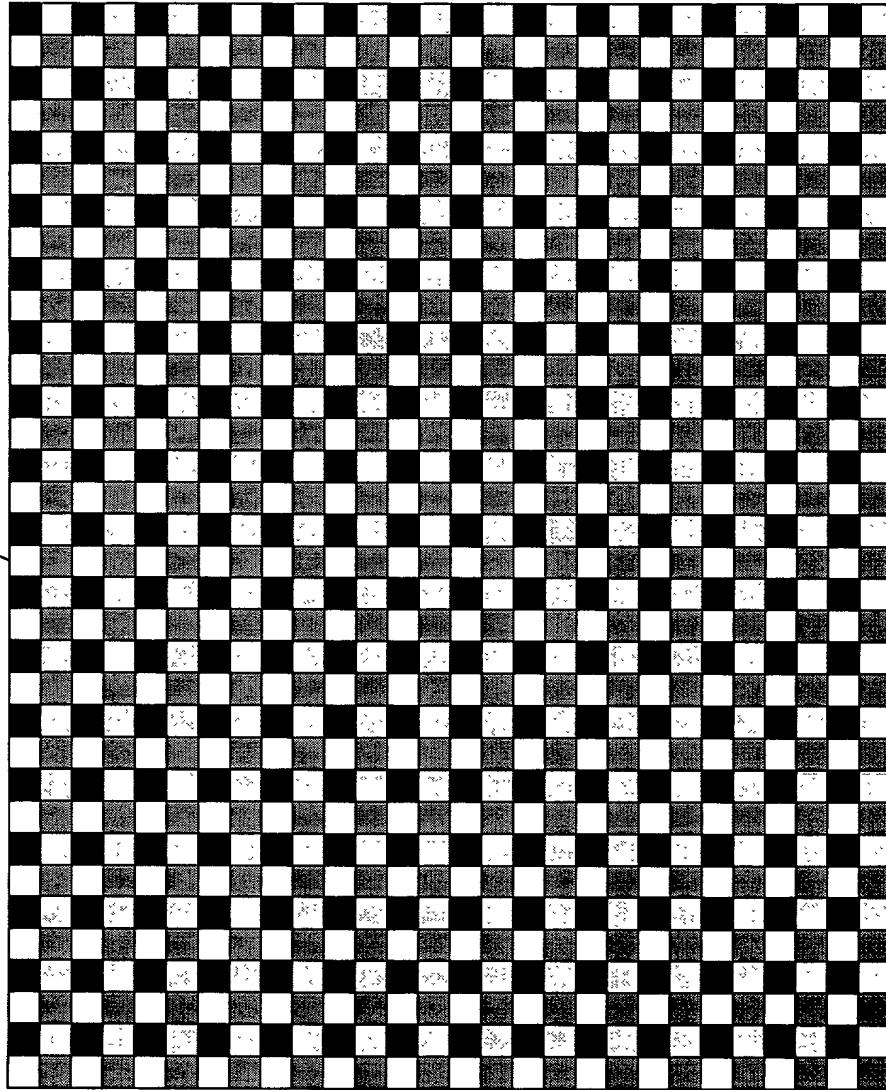
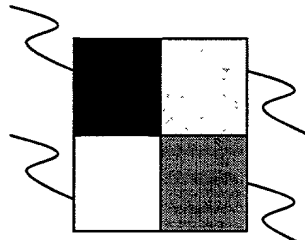


Fig. 4A

102 105



104 103

Fig. 4B

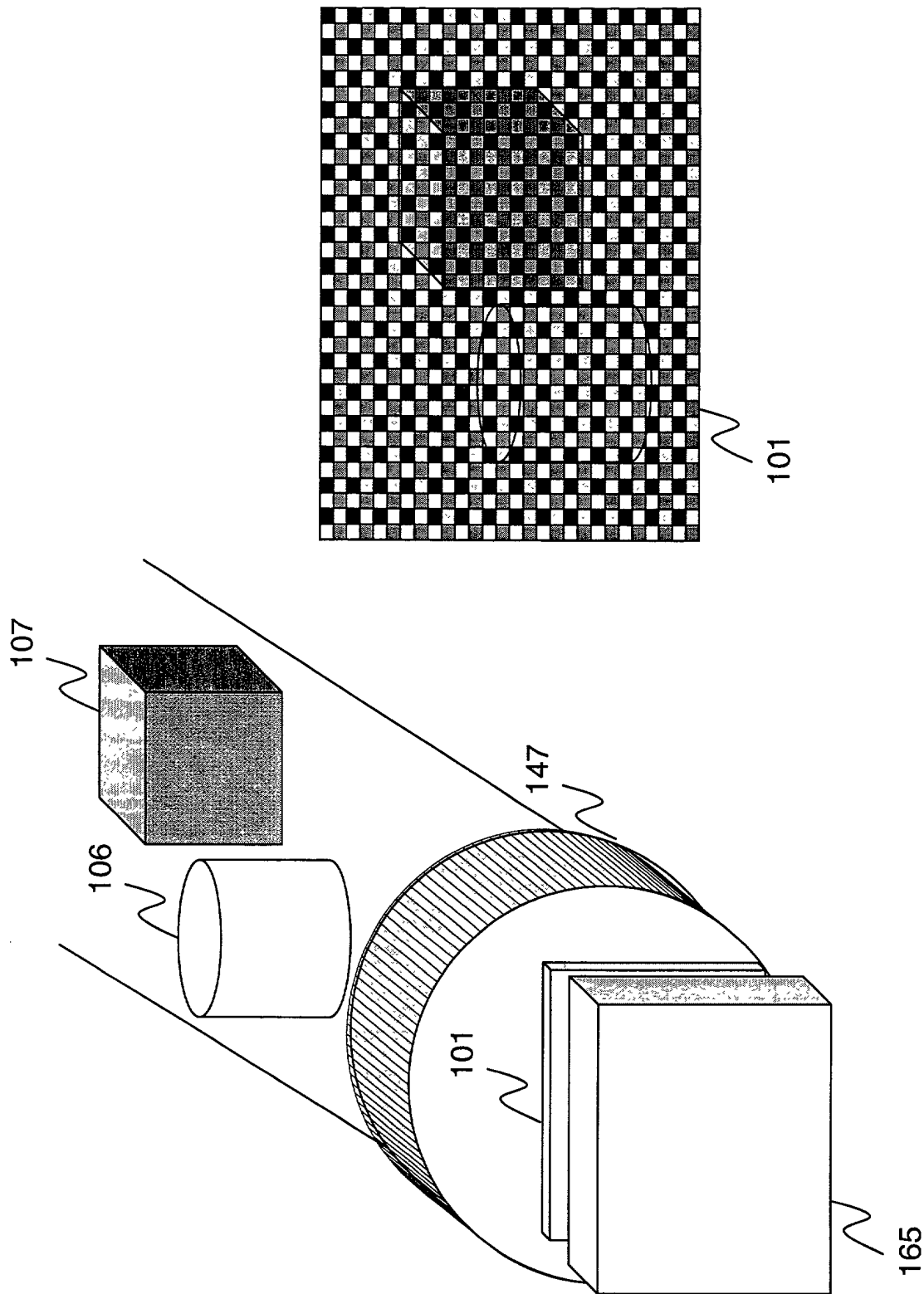


Fig. 5B

Fig. 5A

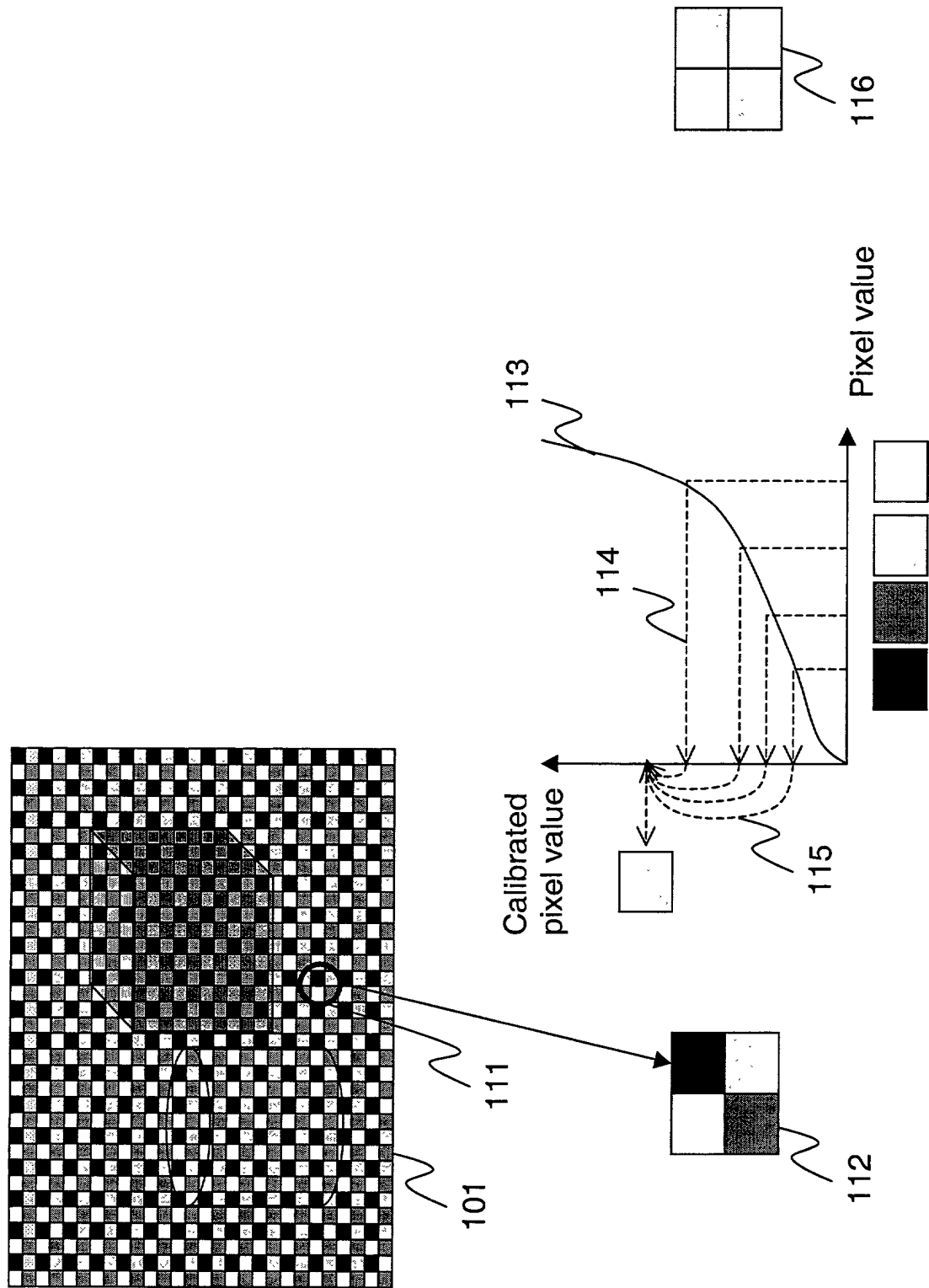


Fig. 6

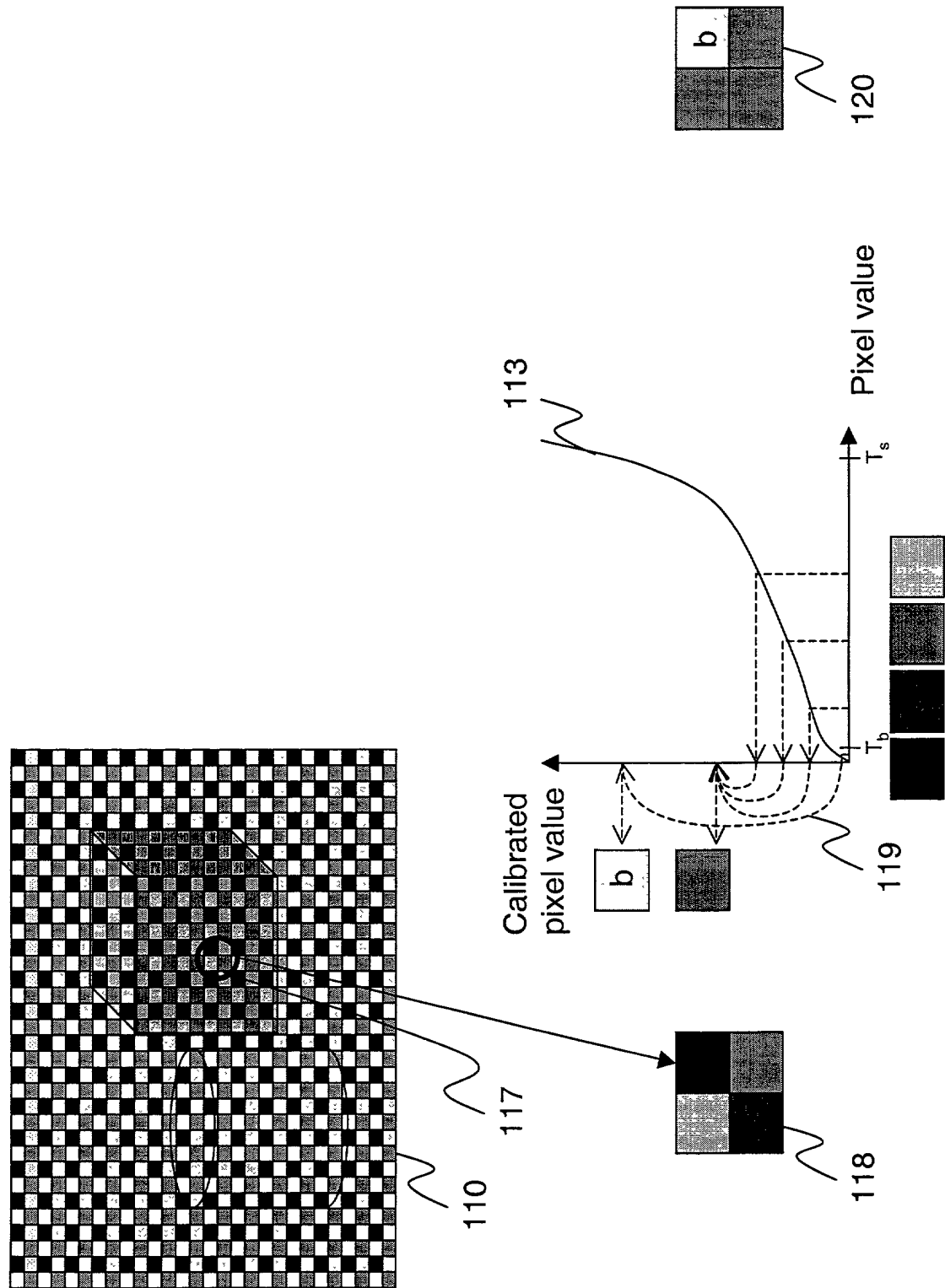


Fig. 7



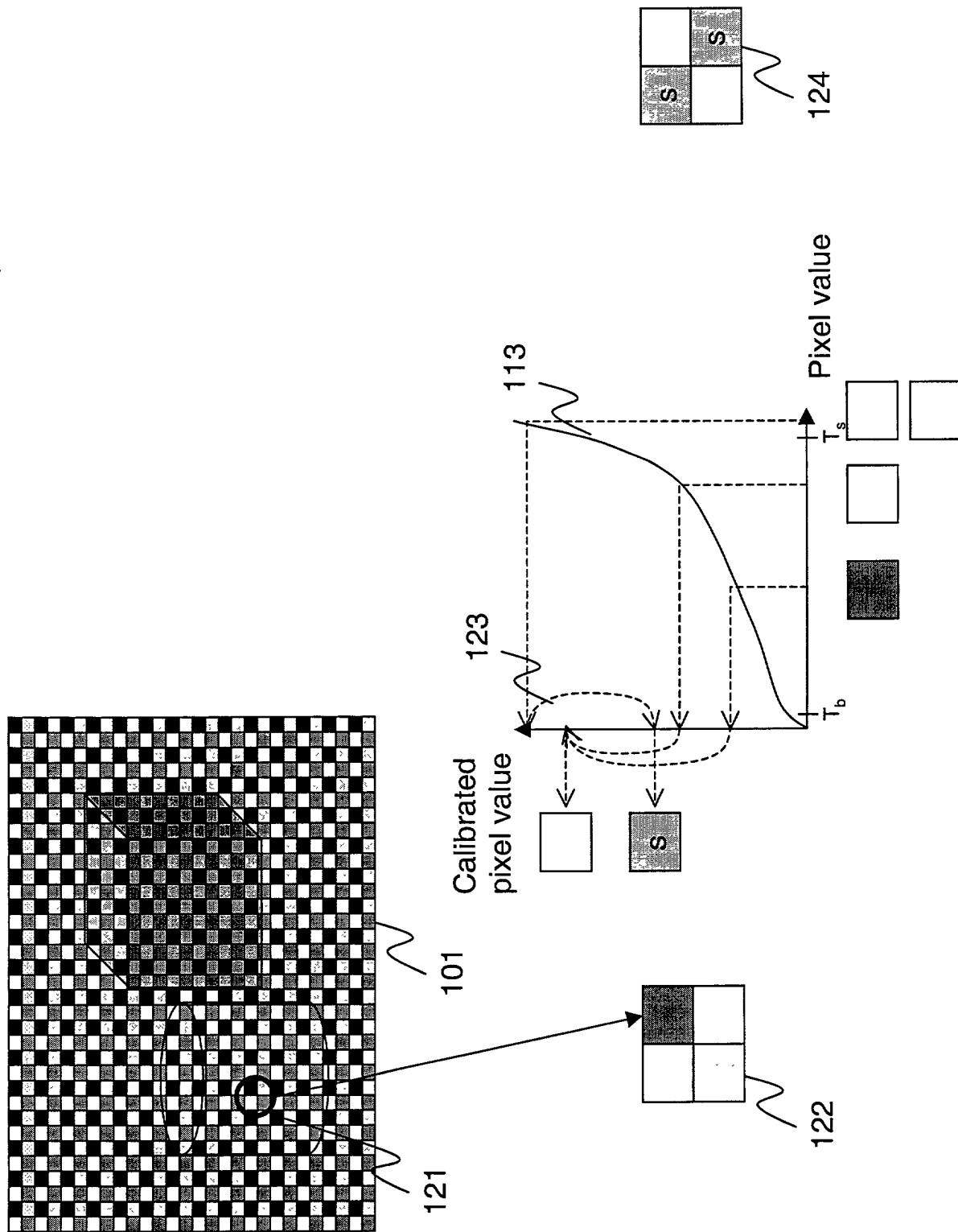


Fig. 8

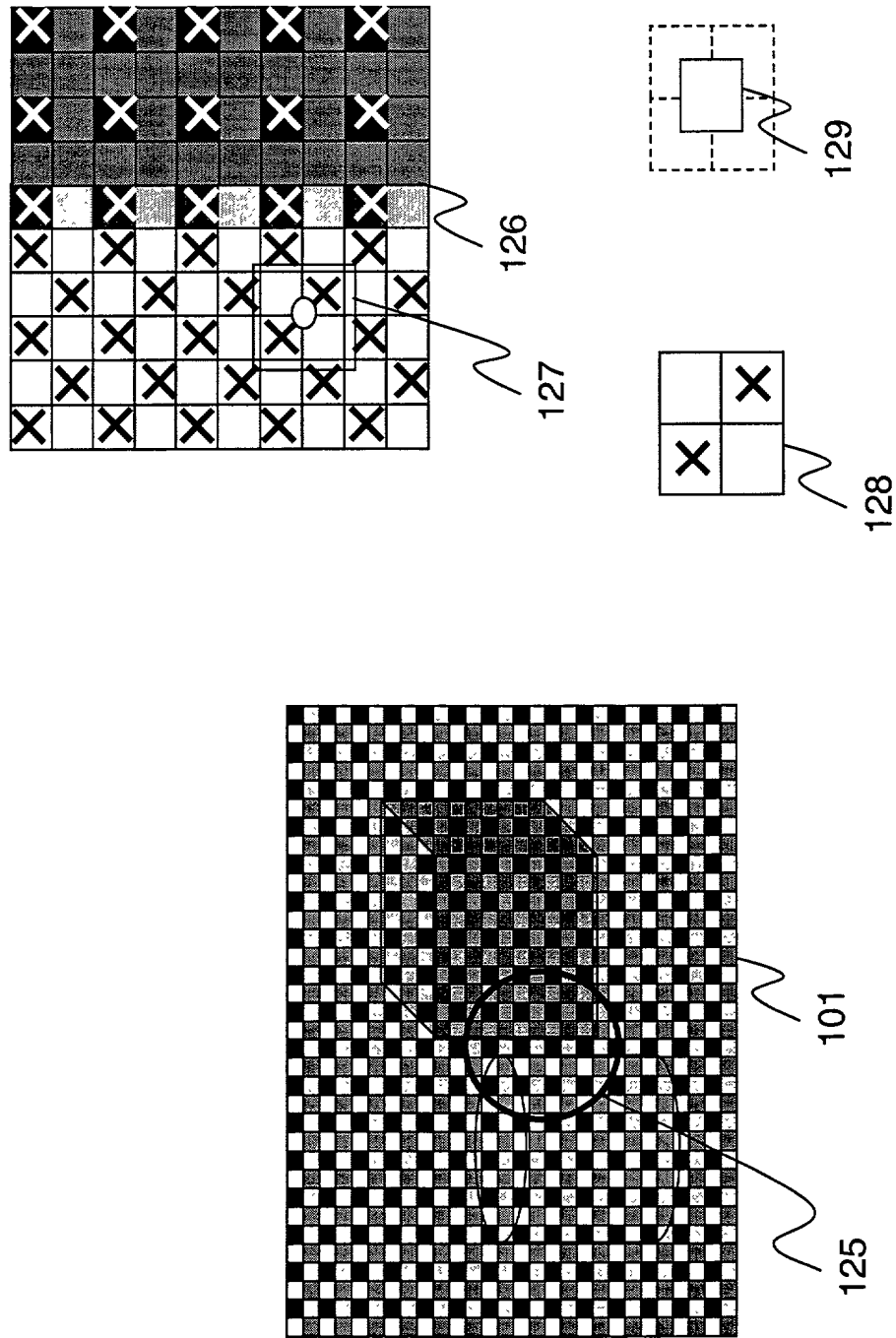


Fig. 9

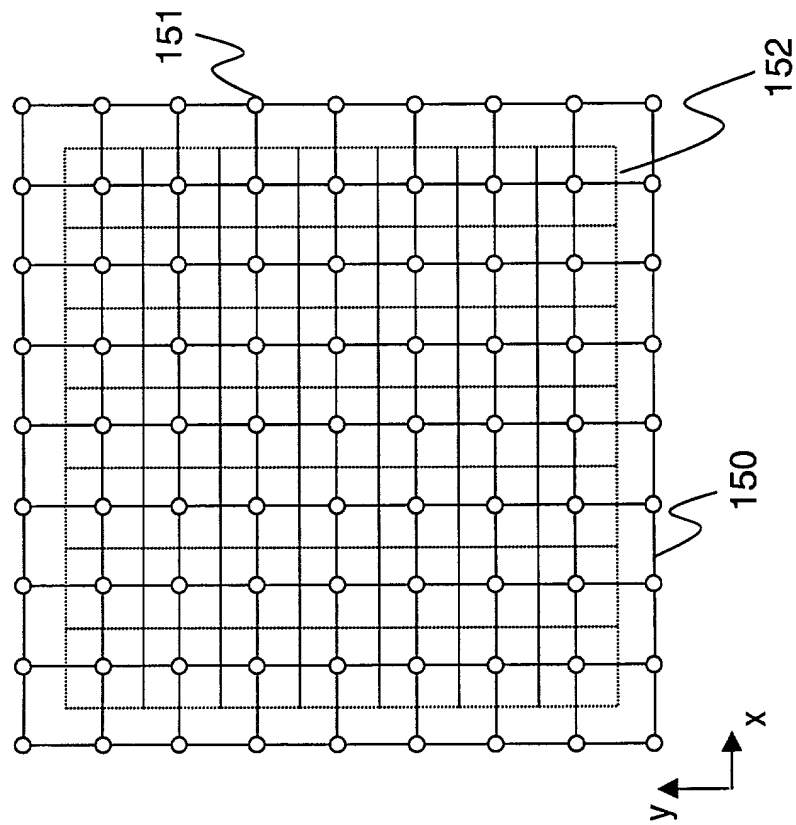


Fig. 10A

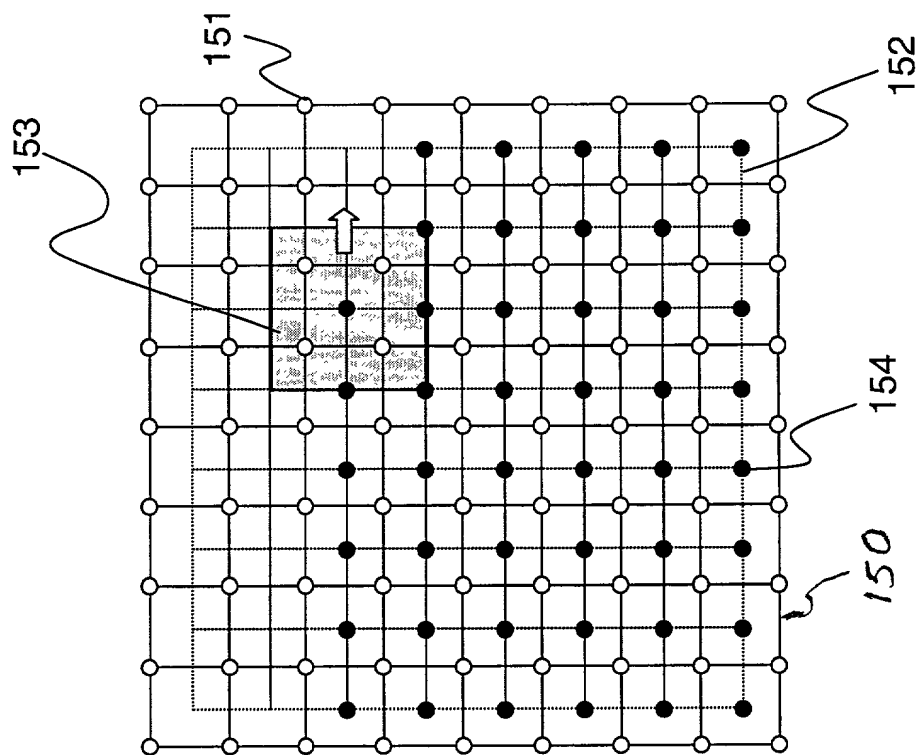
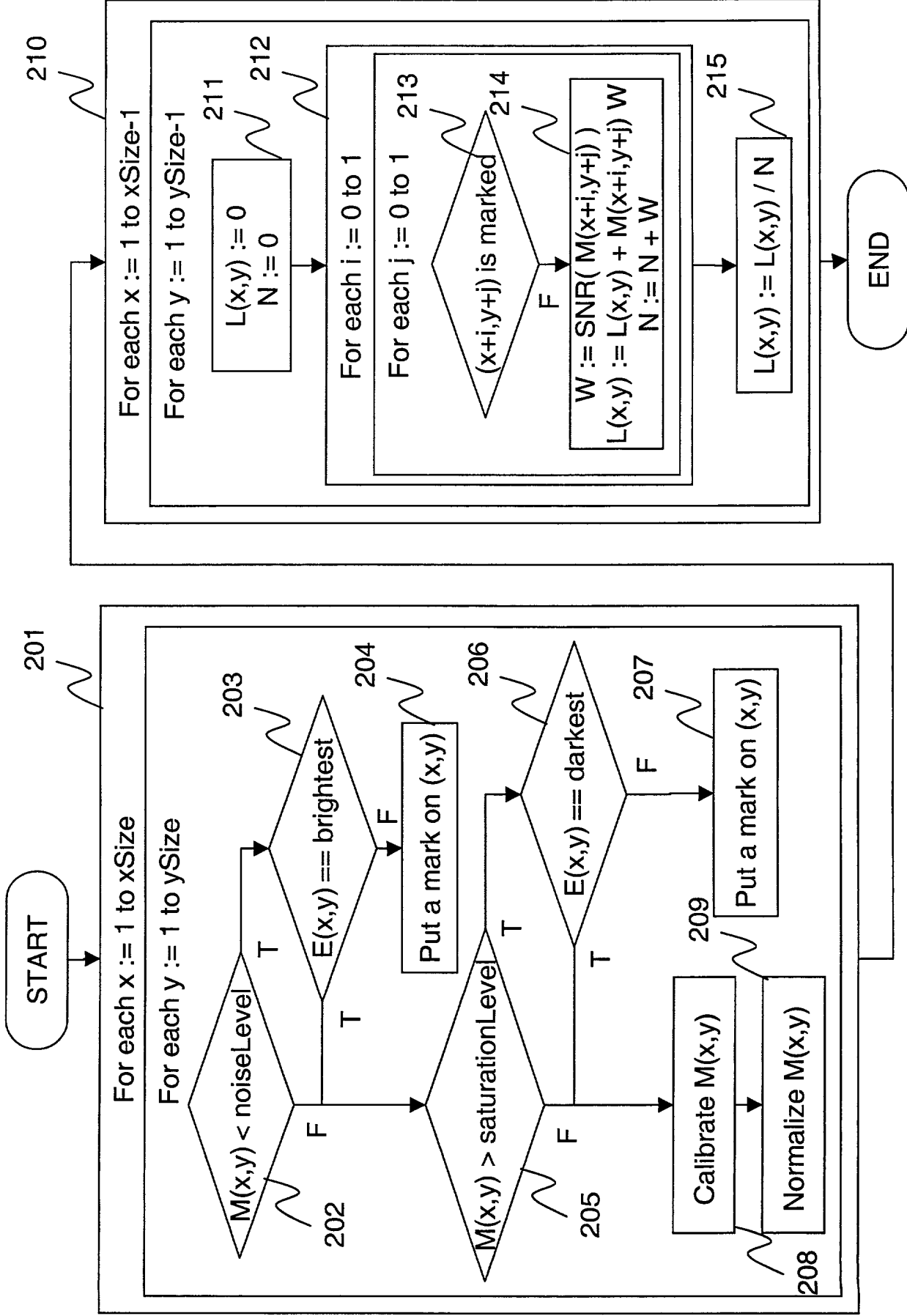
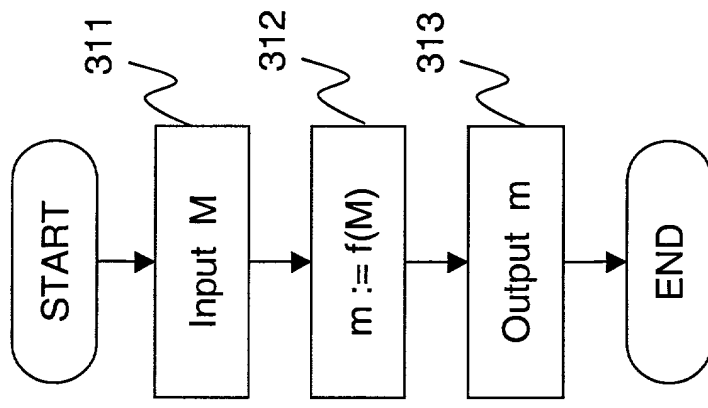


Fig. 10B



300 Fig. 11



310

Fig. 11A

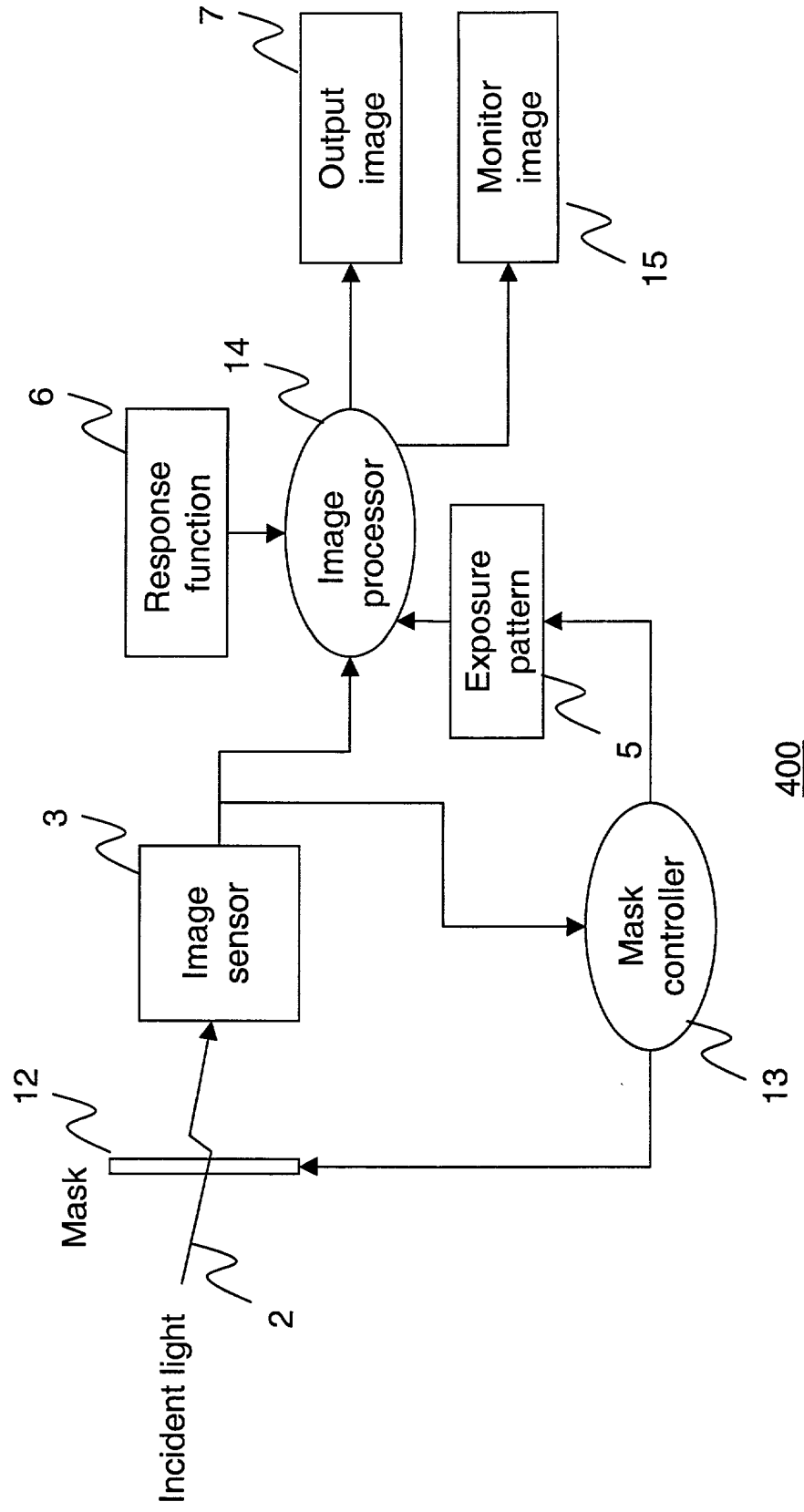
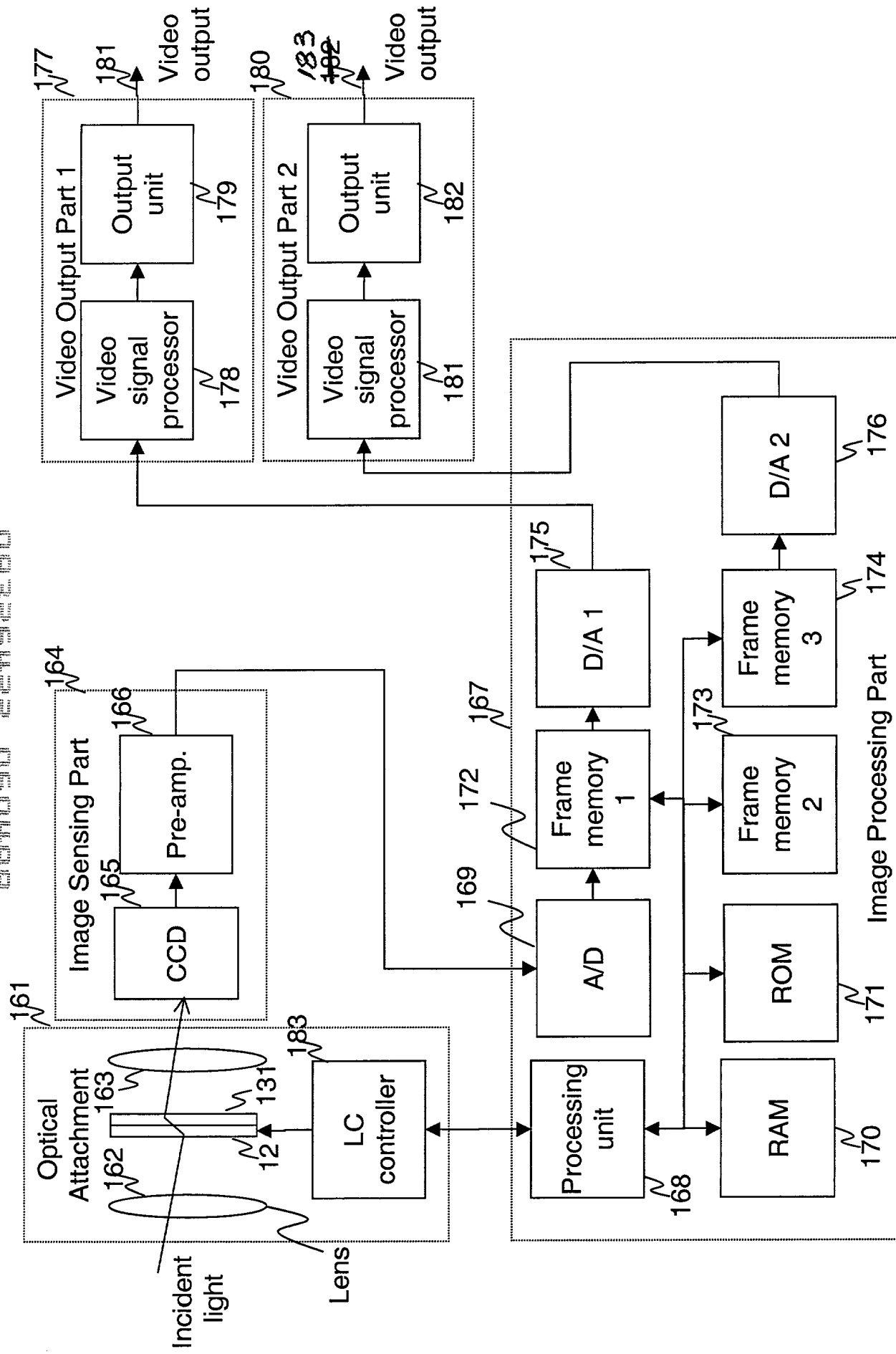
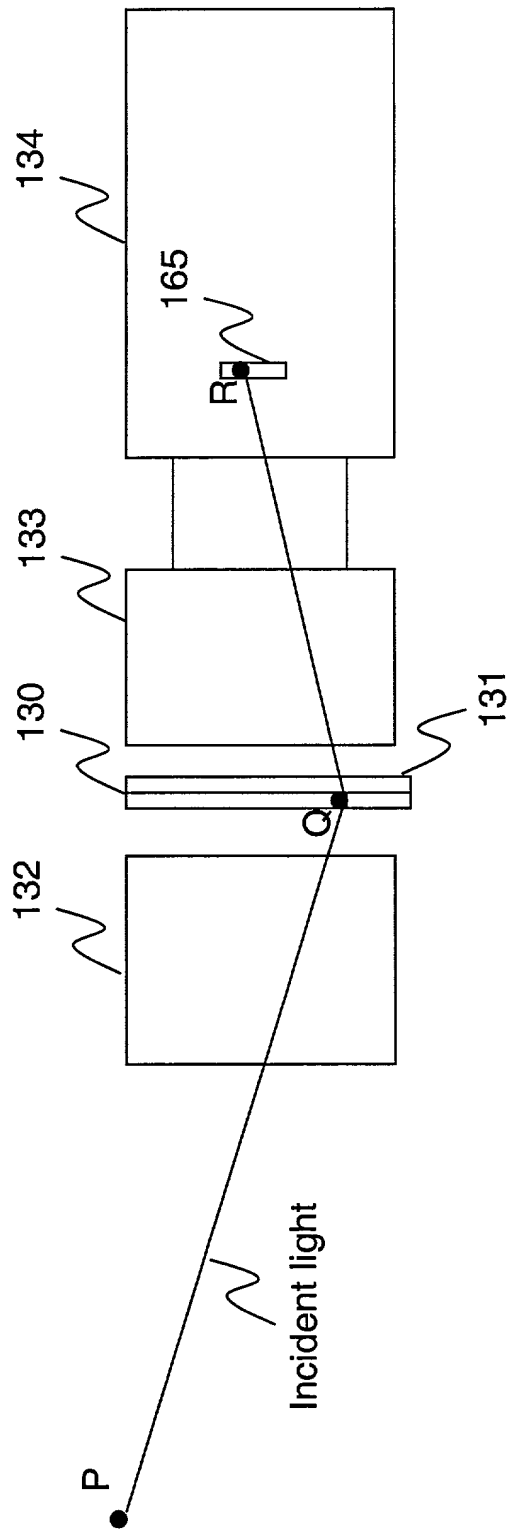


Fig. 12





600

Fig. 14



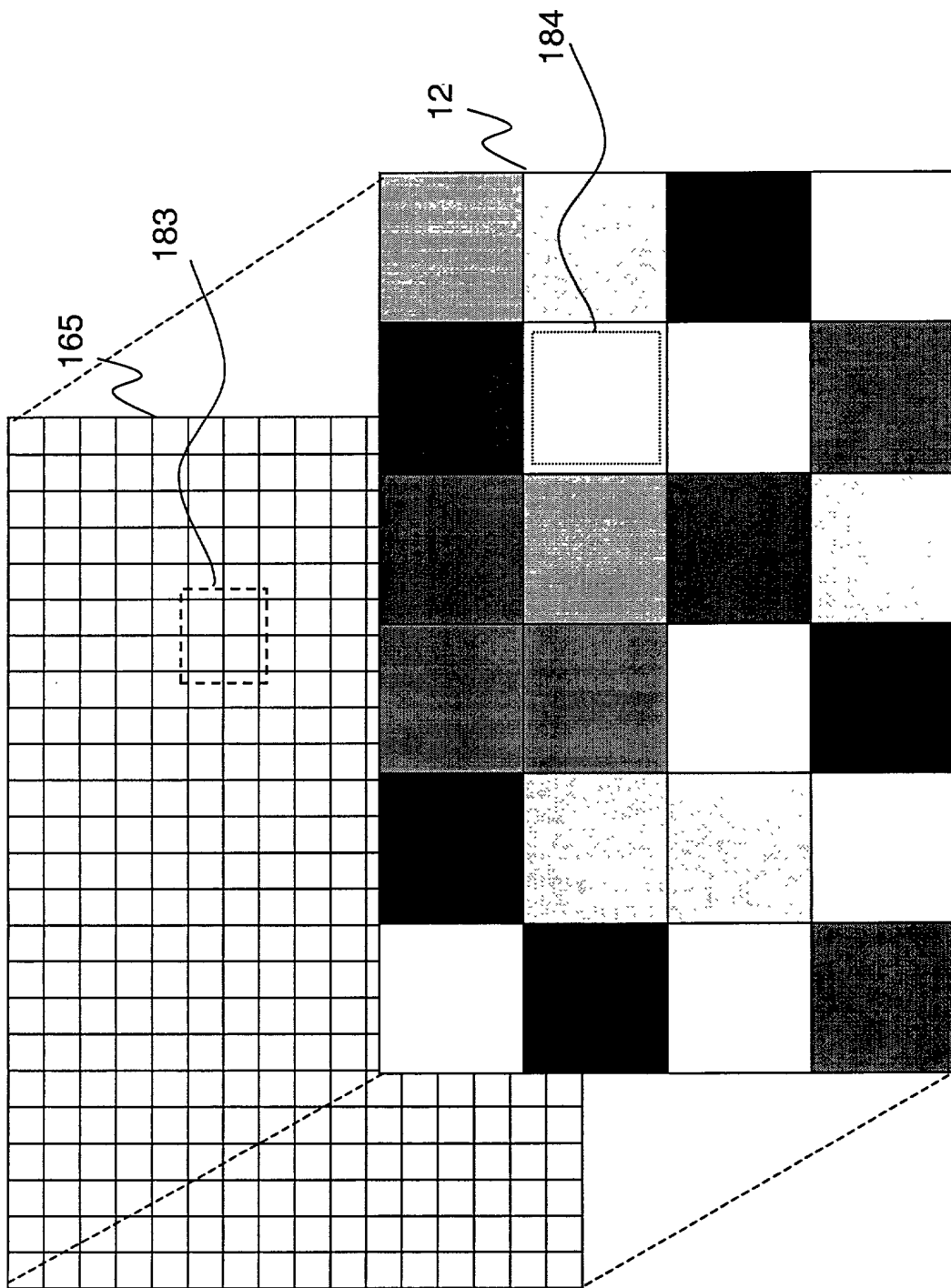


Fig. 15

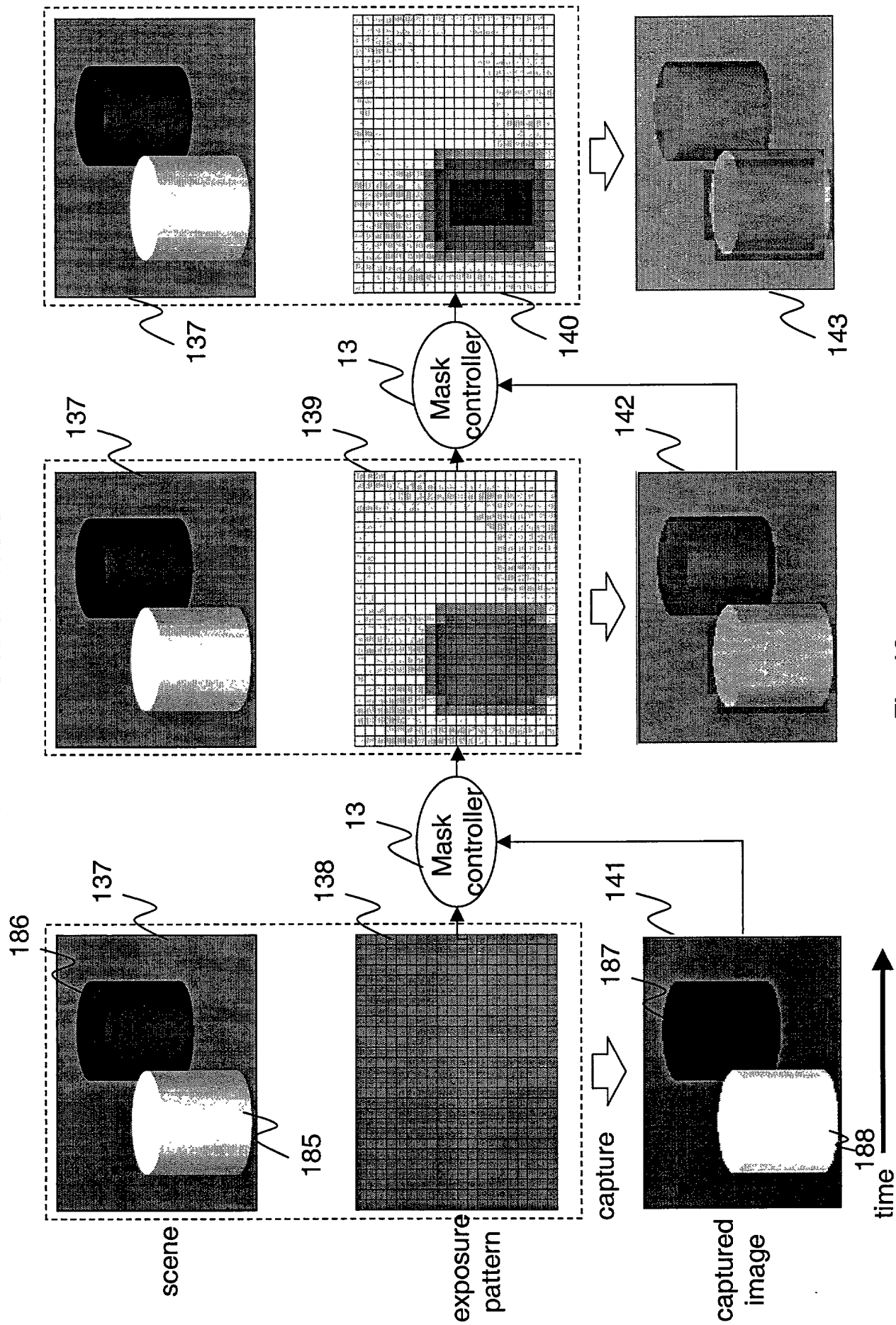


Fig. 16

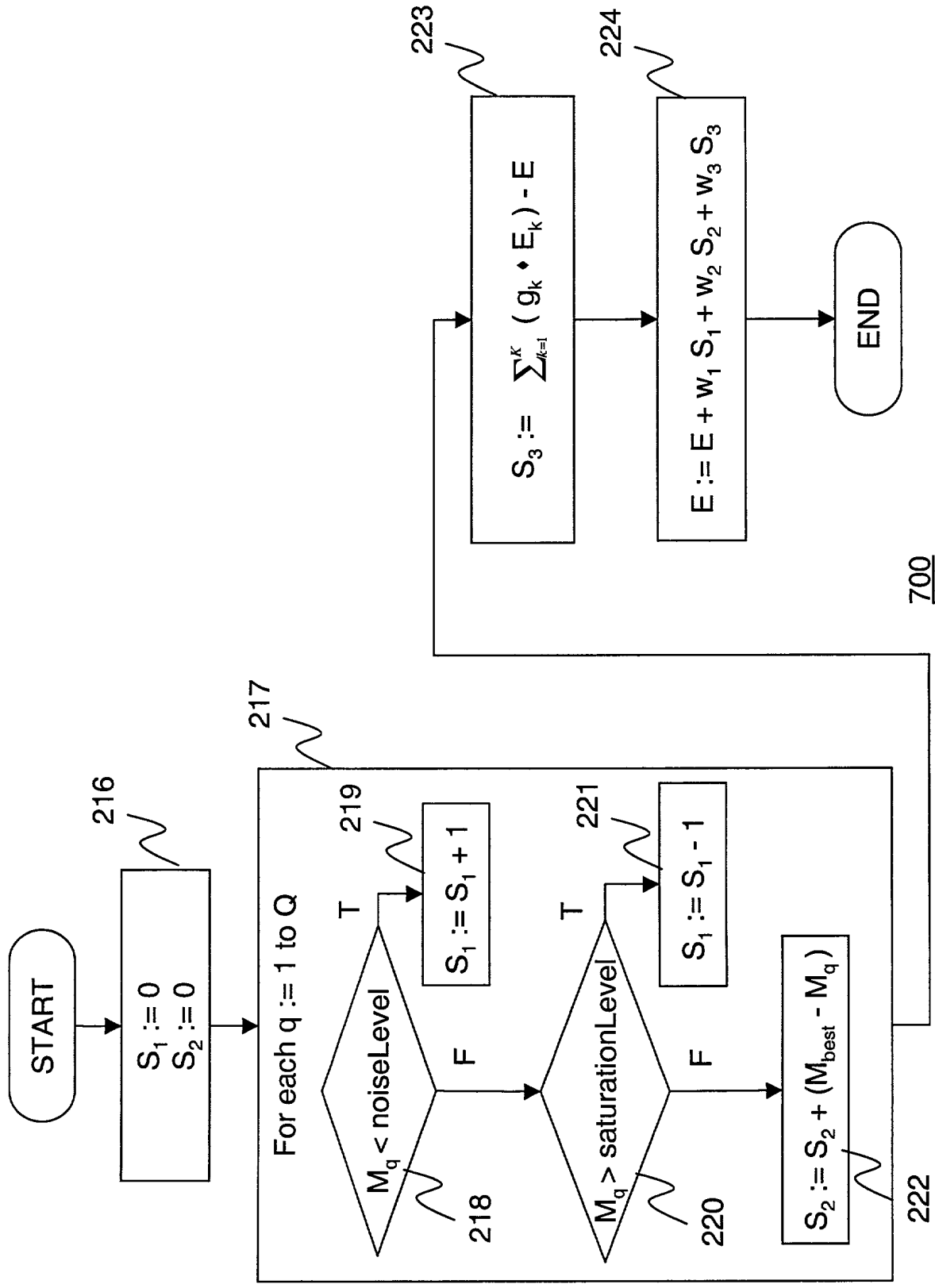
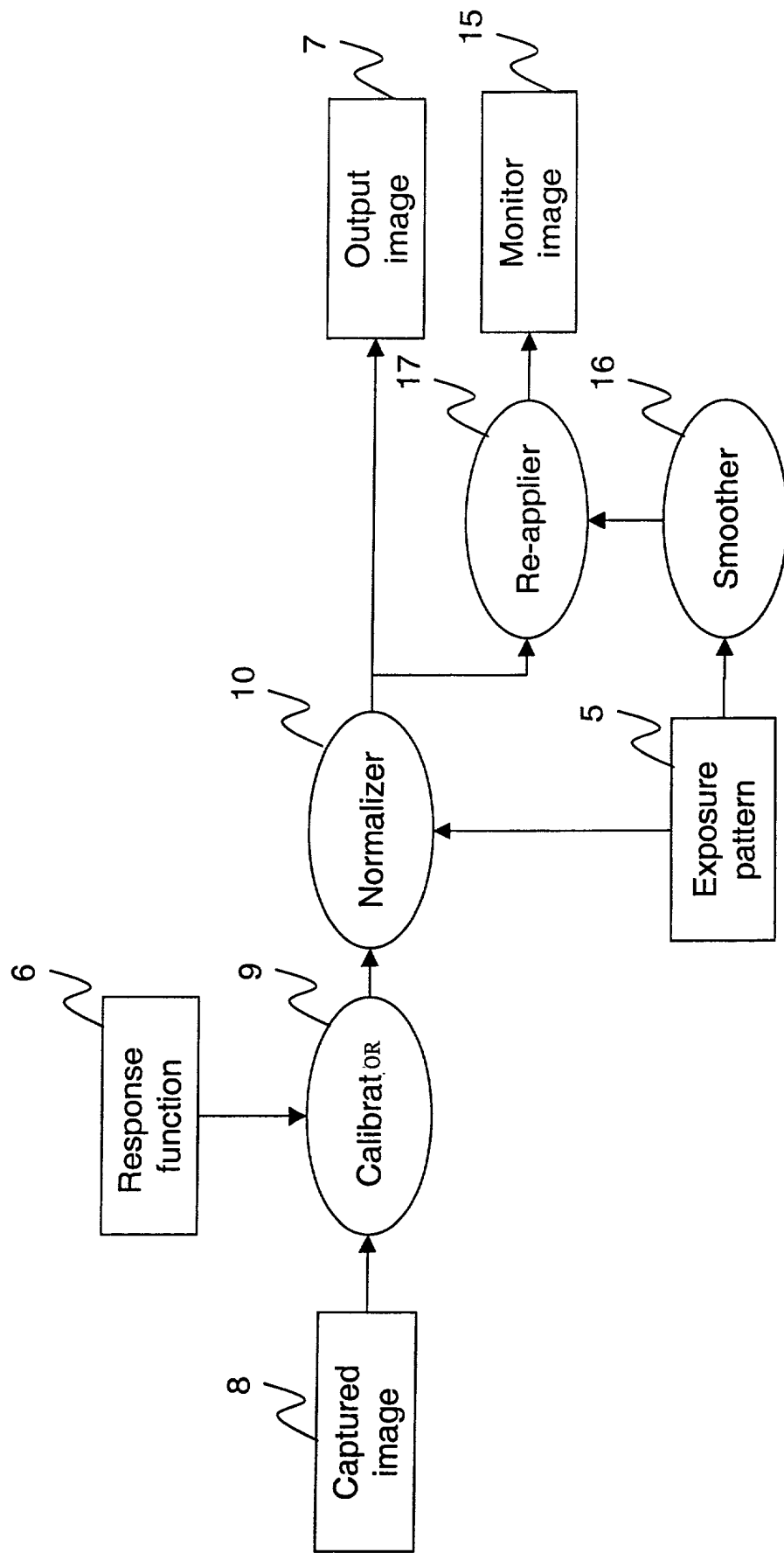


Fig. 17



800

Fig. 18

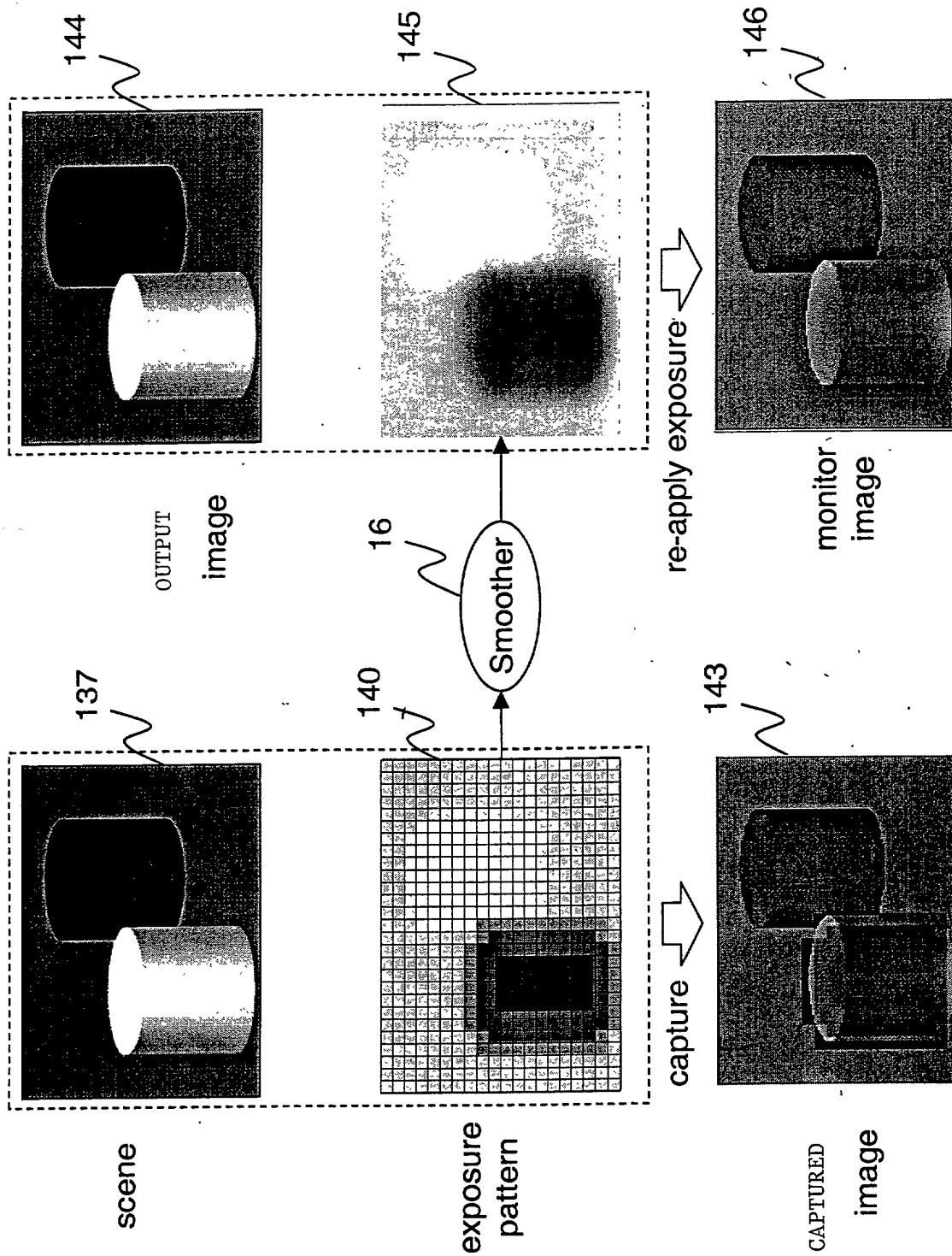


Fig. 19

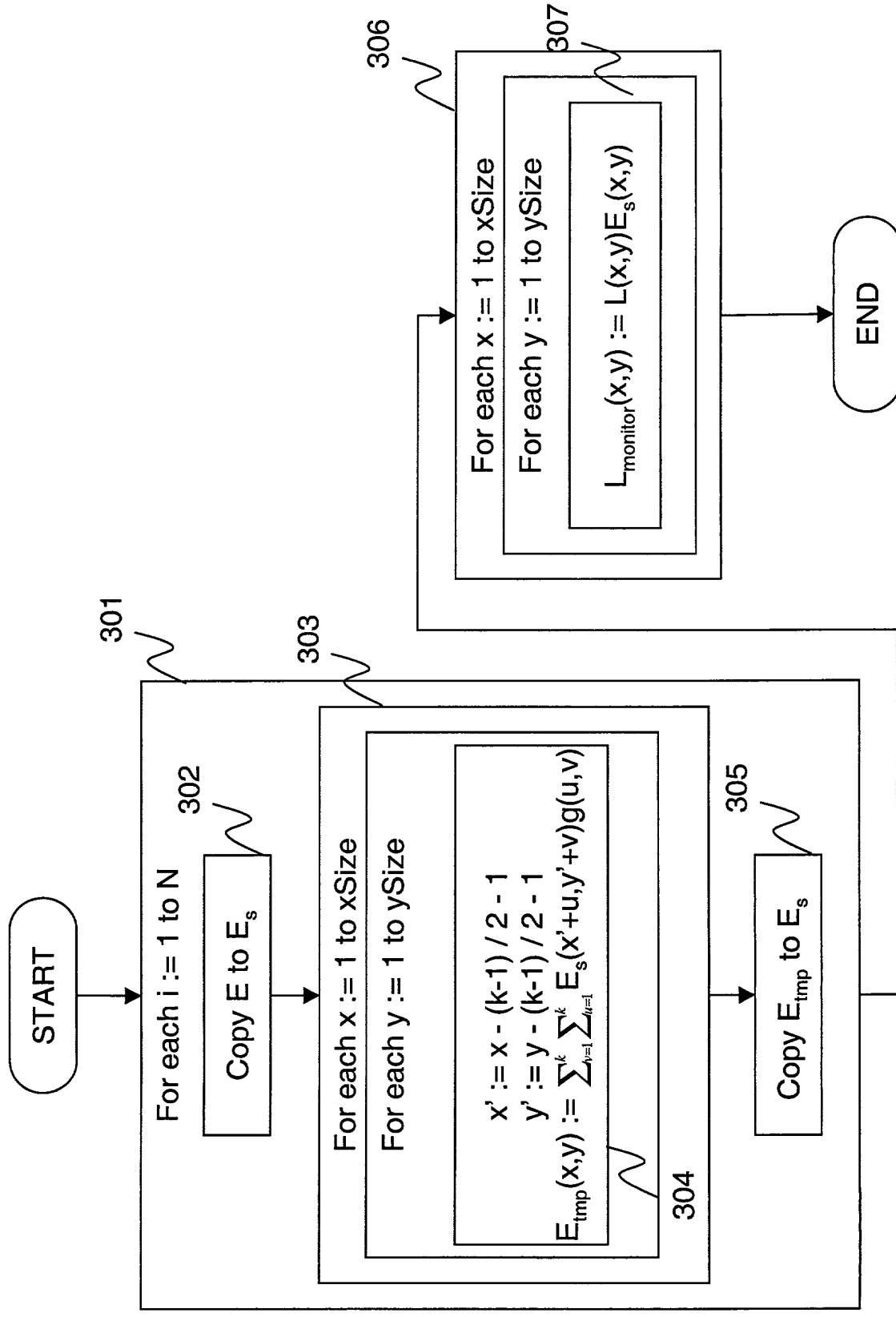
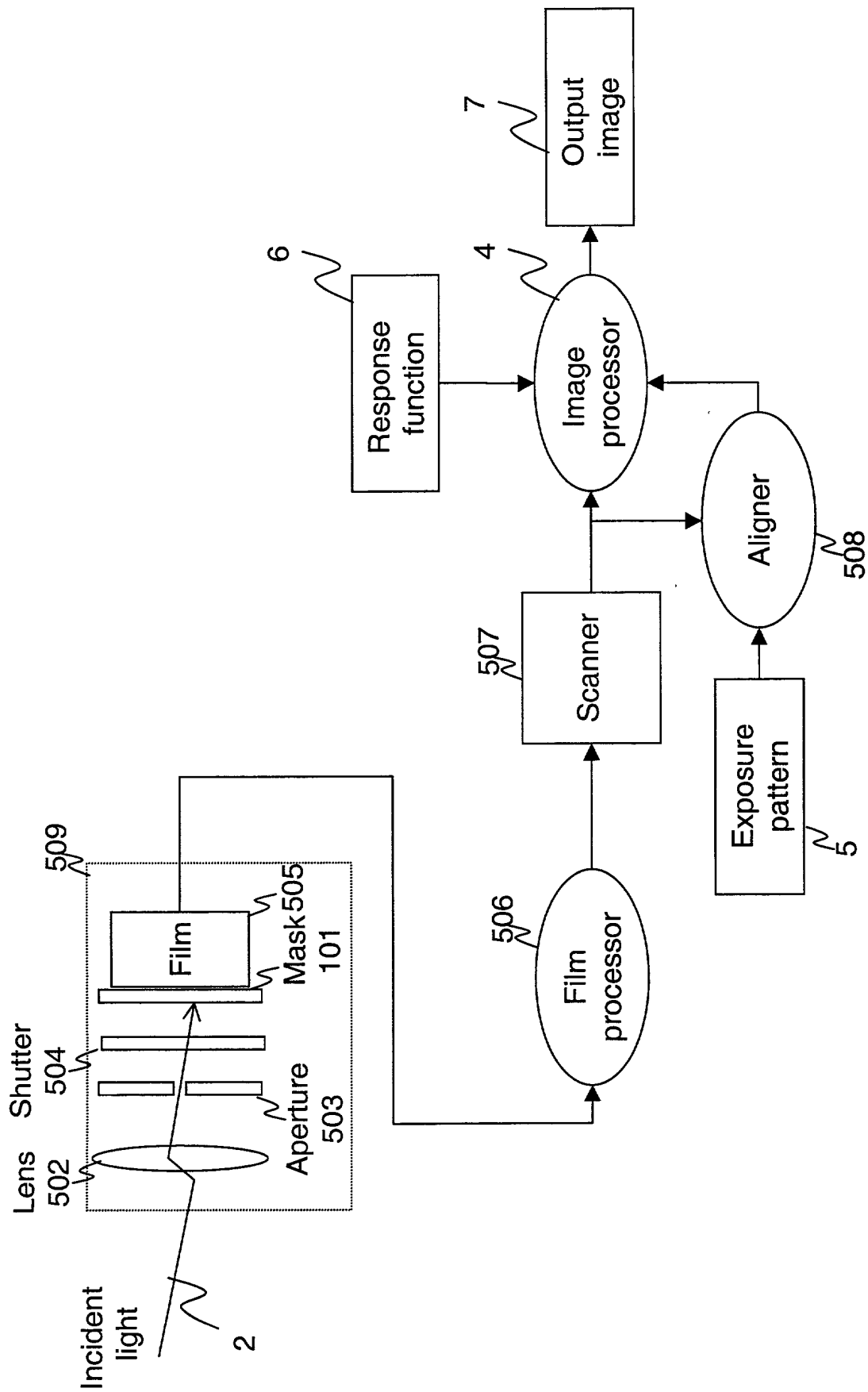


Fig. 20

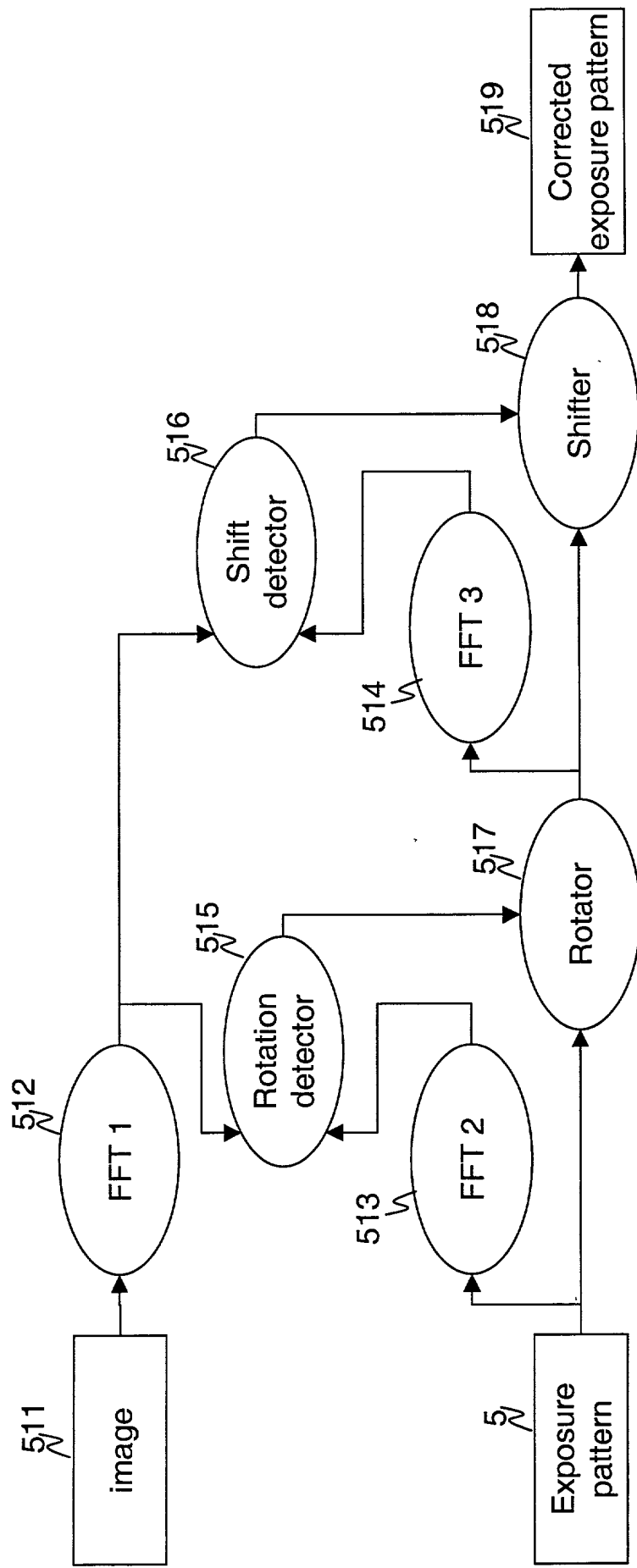
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0.02	0.1	0.16	0.1	0.02
0.0125	0.0625	0.1	0.0625	0.0125
0.0025	0.0125	0.02	0.0125	0.0025

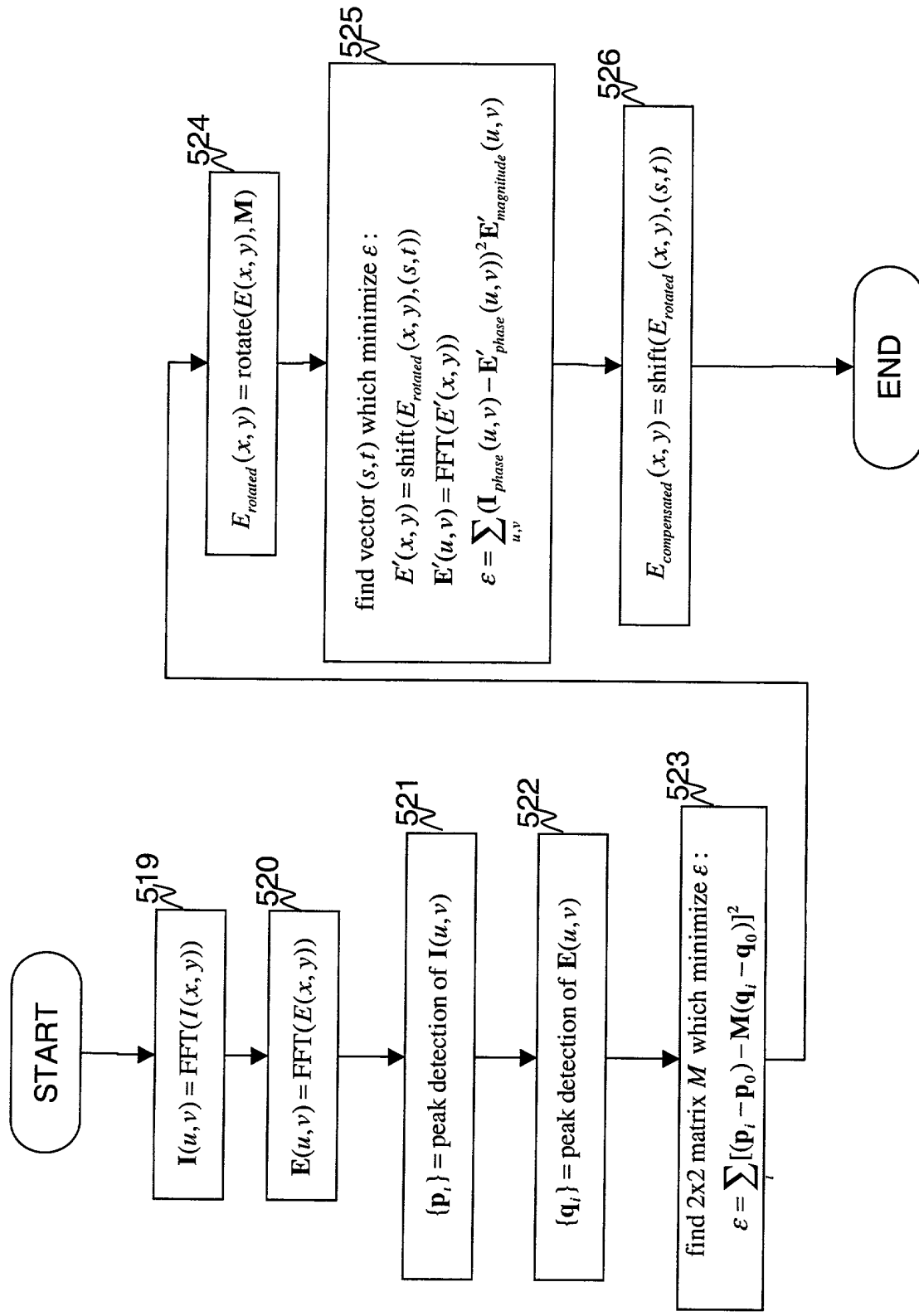
501

Fig. 21









# **COMBINED DECLARATION AND POWER OF ATTORNEY**

**(Original, Design, National Stage of PCT, Divisional, Continuation or C-I-P Application)**

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name; I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

APPARATUS AND METHOD FOR HIGH DYNAMIC RANGE IMAGING USING SPATIALLY VARYING EXPOSURE This declaration is of the following type:

- ☒ original
- ☐ design
- ☐ national stage of PCT.
- ☐ divisional
- ☐ continuation
- ☐ continuation-in-part (C-I-P)

the specification of which: *(complete (a), (b), or (c))*

(a) ☒ is attached hereto.

(b) ☐ was filed on as Application Serial No. and was amended on *(if applicable)*.

(c) ☐ was described and claimed in PCT International Application No. filed on and was amended on *(if applicable)*.

## **Acknowledgement of Review of Papers and Duty of Candor**

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to the patentability of the subject matter claimed in this application in accordance with Title 37, Code of Federal Regulations § 1.56.

☐ In compliance with this duty there is attached an information disclosure statement. 37 CFR 1.98.

## **Priority Claim**

I hereby claim foreign priority benefits under Title 35, United States Code, § 119(a)-(d) of any foreign application(s) for patent or inventor's certificate or of any PCT International Application(s) designating at least one country other than the United States of America listed below and have also identified below any foreign application(s) for patent or inventor's certificate or any PCT International Application(s) designating at least one country other than the United States of America filed by me on the same subject matter having a filing date before that of the application on which priority is claimed

*(complete (d) or (e))*

(d) ☒ no such applications have been filed.

(e) ☐ such applications have been filed as follows:

PRIOR FOREIGN/PCT APPLICATION(S) FILED WITHIN 12 MONTHS (6 MONTHS FOR DESIGN) PRIOR TO SAID APPLICATION			
COUNTRY	APPLICATION NO	DATE OF FILING (day, month, year)	DATE OF ISSUE (day, month, year)
			PRIORITY CLAIMED UNDER 35 USC 119 [ ] YES NO [ ]
			[ ] YES NO [ ]
			[ ] YES NO [ ]
ALL FOREIGN APPLICATION[S], IF ANY, FILED MORE THAN 12 MONTHS (6 MONTHS FOR DESIGN) PRIOR TO SAID APPLICATION			
			[ ] YES NO [ ]
			[ ] YES NO [ ]
			[ ] YES NO [ ]

### Claim for Benefit of Prior U.S. Provisional Application(s)

I hereby claim the benefit under Title 35, United States Code, § 119(e) of any United States provisional application(s) listed below:

Provisional Application Number	Filing Date

### Claim for Benefit of Earlier U.S./PCT Application(s) under 35 U.S.C. 120

*(complete this part only if this is a divisional, continuation or C-I-P application)*

I hereby claim the benefit under Title 35, United States Code, § 120 of any United States application(s) or PCT international application(s) designating the United States of America that is/are listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior application(s) in the manner provided by the first paragraph of Title 35, United States Code § 112, I acknowledge the duty to disclose information as defined in Title 37, Code of Federal Regulations, § 1.56 which occurred between the filing date of the prior application(s) and the national or PCT international filing date of this application:

(Application Serial No )	(Filing Date)	(Status) (patented, pending, abandoned)
(Application Serial No )	(Filing Date)	(Status) (patented, pending, abandoned)

### Power of Attorney

As a named inventor, I hereby appoint Dana M. Raymond, Reg. No. 18,540; Frederick C. Carver, Reg. No. 17,021; Francis J. Hone, Reg. No. 18,662; Joseph D. Garon, Reg. No. 20,420; Arthur S. Tenser, Reg. No. 18,839; Ronald B. Hildreth, Reg. No. 19,498; Thomas R. Nesbitt, Jr., Reg. No. 22,075; Robert Neuner, Reg. No. 24,316; Richard G. Berkley, Reg. No. 25,465; Richard S. Clark, Reg. No. 26,154; Bradley B. Geist, Reg. No. 27,551; James J. Maune, Reg. No. 26,946; John D. Murnane, Reg. No. 29,836; Henry Tang, Reg. No. 29,705; Robert C. Scheinfeld, Reg. No. 31,300; John A. Fogarty, Jr., Reg. No. 22,348; Louis S. Sorell, Reg. No. 32,439; Rochelle K. Seide Reg. No. 32,300; Gary M. Butter, Reg. No. 33,841; Marta E. Delsignore, Reg. No. 32,689; and Lisa B. Kole, Reg. No. 35,225 of the firm of BAKER & BOTTS, L.L.P., with offices at 30 Rockefeller Plaza, New York, New York 10112, as attorneys to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith

SEND CORRESPONDENCE TO: BAKER & BOTTS, L.L.P. 30 ROCKEFELLER PLAZA, NEW YORK, N.Y. 10112 CUSTOMER NUMBER: 21003	DIRECT TELEPHONE CALLS TO: BAKER & BOTTS, L.L.P. (212) 705-5000
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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge

that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

FULL NAME OF SOLE OR FIRST INVENTOR	LAST NAME Nayar	FIRST NAME Shree	MIDDLE NAME K.	
RESIDENCE & CITIZENSHIP	CITY New York	STATE or FOREIGN COUNTRY New York	COUNTRY OF CITIZENSHIP U.S.	
POST OFFICE ADDRESS	POST OFFICE ADDRESS 560 Riverside Drive	CITY New York	STATE or COUNTRY NY	ZIP CODE 10027
DATE June 3, 1999	SIGNATURE OF INVENTOR <i>[Signature]</i>			
FULL NAME OF SECOND JOINT INVENTOR, IF ANY	LAST NAME Mitsunaga	FIRST NAME Tomoo	MIDDLE NAME	
RESIDENCE & CITIZENSHIP	CITY New York	STATE or FOREIGN COUNTRY New York	COUNTRY OF CITIZENSHIP Japan	
POST OFFICE ADDRESS	POST OFFICE ADDRESS 140 West 69 <sup>th</sup> Street	CITY New York	STATE or COUNTRY NY	ZIP CODE 10023
DATE June 3, 1999	SIGNATURE OF INVENTOR <i>[Signature]</i>			
FULL NAME OF THIRD JOINT INVENTOR, IF ANY	LAST NAME	FIRST NAME	MIDDLE NAME	
RESIDENCE & CITIZENSHIP	CITY	STATE or FOREIGN COUNTRY	COUNTRY OF CITIZENSHIP	
POST OFFICE ADDRESS	POST OFFICE ADDRESS	CITY	STATE or COUNTRY	ZIP CODE
DATE	SIGNATURE OF INVENTOR			
FULL NAME OF FOURTH JOINT INVENTOR, IF ANY	LAST NAME	FIRST NAME	MIDDLE NAME	
RESIDENCE & CITIZENSHIP	CITY	STATE or FOREIGN COUNTRY	COUNTRY OF CITIZENSHIP	
POST OFFICE ADDRESS	POST OFFICE ADDRESS	CITY	STATE or COUNTRY	ZIP CODE
DATE	SIGNATURE OF INVENTOR			
FULL NAME OF FIFTH JOINT INVENTOR, IF ANY	LAST NAME	FIRST NAME	MIDDLE NAME	
RESIDENCE & CITIZENSHIP	CITY	STATE or FOREIGN COUNTRY	COUNTRY OF CITIZENSHIP	
POST OFFICE ADDRESS	POST OFFICE ADDRESS	CITY	STATE or COUNTRY	ZIP CODE
DATE	SIGNATURE OF INVENTOR			
FULL NAME OF SIXTH JOINT INVENTOR, IF ANY	LAST NAME	FIRST NAME	MIDDLE NAME	
RESIDENCE & CITIZENSHIP	CITY	STATE or FOREIGN COUNTRY	COUNTRY OF CITIZENSHIP	
POST OFFICE ADDRESS	POST OFFICE ADDRESS	CITY	STATE or COUNTRY	ZIP CODE
DATE	SIGNATURE OF INVENTOR			